BROWN BOVERI REVIEW

B

Silicon Rectifiers

Part of the silicon rectifier installation in the Aluminium Works, Martigny, Switzerland
Rated 36 kA, 350 V, for the electrolysis of aluminium

Measuring the voltage distribution in the cabinets.

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PREFACE

After research into semiconductors during the 1930's had succeeded in establishing their basic theory and, later, led to the preparation of the materials in an extremely pure state, especially silicon and germanium, the foundations had been laid for the industrial utilization of this new scientific knowledge. At that time, when the latent possibilities of semiconductor techniques began to crystallize out, Brown Boveri decided to include this promising field in their electrical programme and to undertake research of their own, in order to establish a foundation for a completely independent technique and reliable manufacture.

Whereas the scientific investigations were carried out on a broad front, corresponding to the widespread nature of the problems, development work was confined to that field in which Brown Boveri have a long-established reputation: namely, the conversion of current. To begin with, germanium power diodes were developed and successfully commissioned in a number of installations. Investigations carried out at the same time on a comparative basis into silicon and its suitability showed, however, that its use offered appreciable advantages for power diodes, with the result that development was next concentrated on a high-power silicon diode. When this element had also been placed in practical operation, it was possible to forge ahead with the development of a controlled silicon rectifier—or silicon thyratron—to such an extent that it is now ready for manufacture.

The evolution of the semiconductor rectifiers took place at a time when the other kinds of rectifiers, such as gaseous discharge vessels and mechanical rectifiers, had long reached their full maturity. In order not to begin at a disadvantage relative to the other kinds, every effort had to be made to render the semiconductor rectifiers

as reliable as stipulated for electrolysis plants. This was made all the more necessary by the fact that, in addition to their outstanding advantages, the semiconductor valves suffer from the inevitable weakness of having only a limited overload capacity. This peculiarity has given rise to a completely new strategy in the circuitry, features of which are the high sensitivity and rapid response of the protective devices, as underlined by the slogan "a semiconductor installation is as good as its protective gear". Apart from this development, Brown Boveri have adhered to their tradition of devoting the closest possible attention to the reliability inherent in the nature of the valve itself. A very strict test procedure, evolved quite independently, ensures that only absolutely perfect valves reach practical installations.

In the present special number, the silicon diode is first described, followed by all the questions associated with its proper employment. But since the silicon thyratron is introduced, in addition to the diode, it is necessary to outline the probable fields of application of these two high-power valves, and to predict their prospects in practice. This touches on future problems which, like any prognosis, involves some uncertainty so that, as future development proceeds, it will have to be constantly reviewed.

It is hoped that the contributions in this number will convince readers that Brown Boveri have been successful in their endeavours to evolve a semiconductor technique of their own, and are willing and able to offer their customers their very best in this new field.

(KME) T. WASSERRAB

THE BROWN BOVERI HIGH-POWER SILICON DIODE

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In recent years great progress has been made with germanium and, in particular, silicon diodes. After briefly examining the reason for this, the author outlines the principle of the pn rectifier and the specific effects on its performance in service. The Brown Boveri development programme for semiconductor rectifiers progressed from a germanium element rated 100 A, 120 V to a silicon high-power element with a mean direct-current rating of 200 A and a normal inverse voltage of 600 V. The article also gives the operating characteristics and other features of this high-power diode.

ELECTRICAL ENERGY is nowadays conveyed from place to place almost exclusively in the form of alternating current. However, a large proportion of the users require energy in the form of direct current. This category of users, which includes the electrochemical industry, high-power industrial drives, as well as many traction vehicles, is continually growing in importance and now consumes about 20% of all the energy generated. The stipulation of maximum possible efficiency in the conversion from a.c. to d.c. led from the classical motor-generator to the development of the mercury-arc rectifier for the higher voltages, while the mechanical rectifier is capable of handling loads requiring only a few hundred volts. In the low-power field the principal elements used were tube rectifiers and, above all, selenium cells.

Although the high efficiency of the mechanical rectifier can hardly be bettered, on account of the unavoidable losses in the rectifier transformer and heavy-current conductors, recent years have witnessed rapid progress by semiconductor rectifiers employing germanium and, still more recently, silicon elements. The specific advantages which may be expected with these semiconductor installations are as follows: the ability to connect rectifier units of one design in series or parallel makes it possible for a very wide power range to be covered. Owing to the high power density of the individual diodes, the increasingly imposed stipulation of maximum compactness is fulfilled in an almost ideal manner. Moreover, a silicon rectifier is capable of working at all temperatures likely to be experienced in normal service, from roughly −50 to +50 °C, and is at all times ready for operation immediately. One of the main advantages over mechanical rectifiers is the absence of any moving parts exposed to wear, which forms the basis of an almost unsurpassable simplicity of maintenance and operation, resulting in long life for the installation. The experience gained so far with semiconductor rectifiers confirms these arguments.

Principle of Semiconductor Rectifiers

The rectifying action of a germanium or silicon diode is based on the pn junction[1] expounded by W. Schockley in 1949. Although this principle has already been amply covered in countless scientific and technical publications, it will be briefly described for the sake of completeness.

In contrast to the classic semiconductor elements of selenium or cuprous oxide, the development of which was for the most part empirical, the new diodes were developed in accordance with modern physical knowledge. But one important condition has to be fulfilled, namely the chemical and physical state of the semiconductor must be clearly defined, i.e. only mono-crystalline material of very high purity, or exactly defined content of foreign matter, may be used.

[1] W. SHOCKLEY: Electrons and Holes in Semiconductors. Published by D. van Nostrand Co. Inc., 1950.

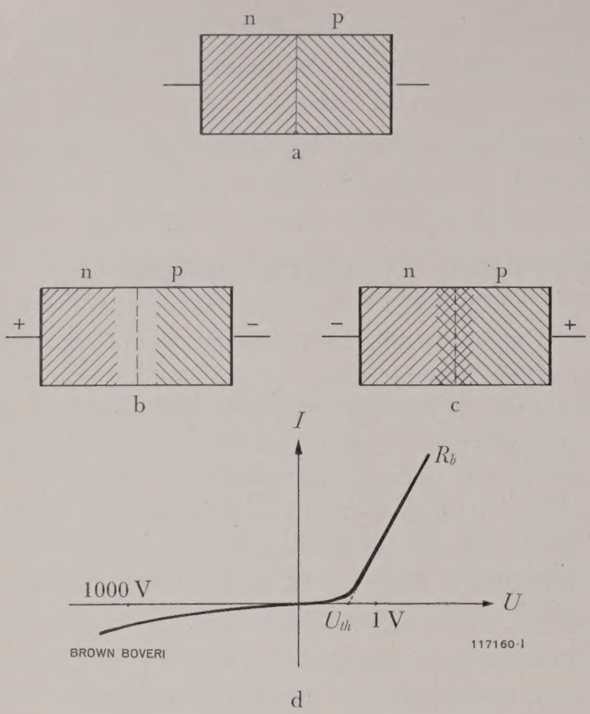

Fig. 1. – Illustrating the principle of a pn rectifier

a: pn crystal without external potential

b: pn crystal polarized in the blocking direction; dislodgement the charge carriers from the junction zone

c: pn crystal polarized in the forward direction; junction zone flooded with carriers

d: current-voltage characteristic
U_{th} = Threshold voltage
R_b = Path resistance

The nature and number of charge carriers is denoted by the shading:
= Electrons
= Holes

In the ideal mono-crystal, which consists entirely of silicon atoms in the tetrahedral arrangement, the passage of current is only possible when electrons are released from their bonds by any suitable input of energy, so that they are free to move. This, for instance, is possible when thermal energy is applied, and is quite pronounced even at room temperature: at the absolute zero a crystal of pure silicon is a complete insulator. A factor which is decisive for the capability of a mono-crystal to conduct asymmetrically is that not only the electrons separated from the atoms help to carry the current, but also the holes thereby produced, in that they are filled up by an immediately adjacent electron. The movement of the hole in the electric field corresponds to that of a positively charged electron and it is therefore treated as if it were a real particle. Thus at a given temperature the ideal semiconductor crystal contains a definite number of pairs of electrons and holes, available for carrying the current; this is known as the intrinsic conductivity of the crystal.

The conductivity can be deliberately controlled by the inclusion of impurities, which either give up electrons to the lattice (n conduction) or bring one electron too few, i.e. provide a hole (p conduction). Materials which yield n conduction are the elements from the fifth group of the periodic system, such as antimony, arsenic or phosphorus; p conduction results when the silicon or germanium is "doped" with elements from the third group, e.g. boron, aluminium or gallium.

If in a particular mono-crystal there is a abrupt change from a region with free electrons (n region) to one with free holes (p region), this is referred to as a pn junction (Fig. 1 a). Its rectifying action may be explained in the following, greatly simplified manner: If a potential is applied to a pn crystal of this kind, so that the p region is negative and the n region accordingly positive (Fig. 1 b), the electrons are attracted to the positive pole, the holes to the negative. This leads to a deficiency of charge carriers at the junction and thus to high resistance. The junction blocks the passage of current.

If, on the other hand, the polarity is reversed (Fig. 1 c), the charge carriers are permitted to enter the junction zone, resulting in low resistance; the diode permits the passage of current.

The relevant current-voltage characteristic is shown in Fig. 1 d. If the resolving power of the characteristic were larger, the current I would rise exponentially at low voltages U. Above the "threshold voltage" U_{th} the characteristic becomes linear, its shape no longer being governed by the pn junction but by the path resistance, i.e. the p or n-conducting zones of the pn crystal in which there is no change in the carrier density, in effect the semiconducting material between the electrode connection and the pn junction.

The blocking characteristic needs more detailed discussion. Firstly the dislodgement of the charge carriers from the junction zone is not complete, but

the semiconductor, by generating new carriers, attempts to restore the forced deviation from the zero-voltage state of equilibrium. Hence, depending on the number of carriers generated per unit time, the inverse current may be high or low. Furthermore, with germanium for example, the amount of energy required to produce a pair of holes at a given temperature is less than for silicon; in other words, the number of pairs produced per s and cm^3 is considerably larger, resulting in an inverse current several orders of magnitude larger than that of a silicon pn junction. But since the number of charge carriers produced per unit time increases exponentially with rising temperature, the same applies to the inverse current. This is most important for the practical application of the rectifiers.

The maximum inverse voltage, or breakdown voltage, is given by the fact that in the zone impoverished of carriers, the field strength may not exceed a definite, critical value. If it is reached, additional carriers are produced in the blocking zone by field or avalanche effects, leading to a steep increase in the inverse current and, particularly with silicon diodes for high inverse voltages, to destruction of the element. This critical field strength is between 300 and 500 kV/cm for silicon. The absolute breakdown voltage thus increases, the larger the blocking zone is. Without going any further into this, it may be mentioned that this can be attained by the inclusion of only a few impurities, i.e. by using high-resistance semiconductor material. Now this leads to a high path resistance in the direction of flow, so that the condition of high inverse voltage and low forward voltage drop, necessary for a power rectifier, cannot be fulfilled by a simple pn junction.

A solution to this problem is afforded by the psn structure put forward by R. N. Hall in 1950 (Fig. 2a).[2] In this case an intermediate zone of high resistance is flanked by an n-conducting zone of low resistance on the one side and a p-conducting zone of low resistance on the other. Regarded in the blocking direction, therefore, there is a pn junction containing a high-resistance zone (shown in Fig. 2 for example as p-conducting, high resistance), permitting the attainment of high inverse voltages, according to what has just been said. In the forward direction the high-resistance intermediate zone is overcome by the penetration of charge carriers from the n and from the p side; as a result this intermediate zone becomes very low in resistance. The highly-doped boundary zones are very short and low in resistance, thus causing a small voltage drop at high current densities.

If a diode is in operation, the charge carriers are dislodged during the blocking phase in the rhythm of the a.c. frequency, while the intermediate zone is

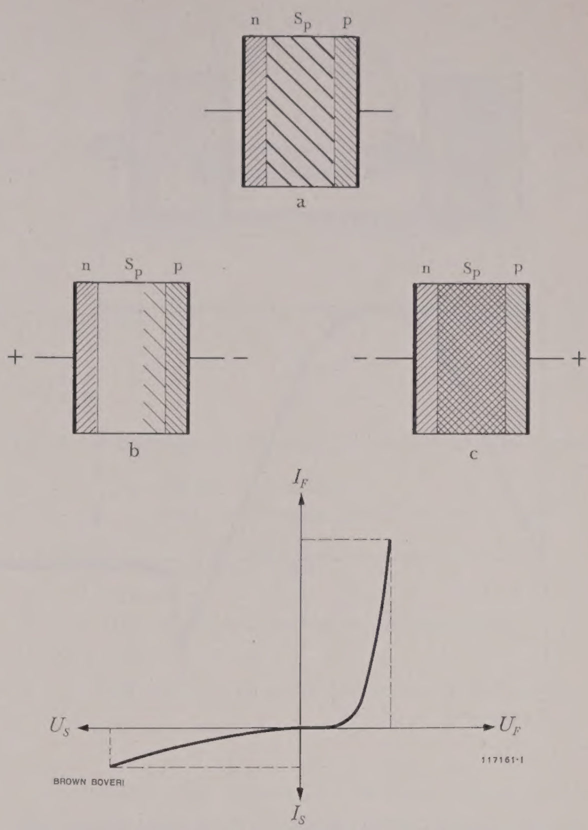

Fig. 2. – Illustrating the principle of a psn rectifier

a: psn crystal without external potential

b: psn crystal polarized in the blocking direction

c: psn crystal polarized in the forward direction; the entire intermediate zone is flooded with charge carriers

d: current-voltage characteristic

I_F = Forward current
I_S = Inverse current
U_F = Forward voltage
U_S = Inverse voltage

The shading denotes:
= Electrons
= Holes

[2] R. N. HALL and W. C. DUNLAP: P–N Junctions prepared by Impurity Diffusion. Phys. Rev. 1950, Vol. 80, No. 3, p. 467.

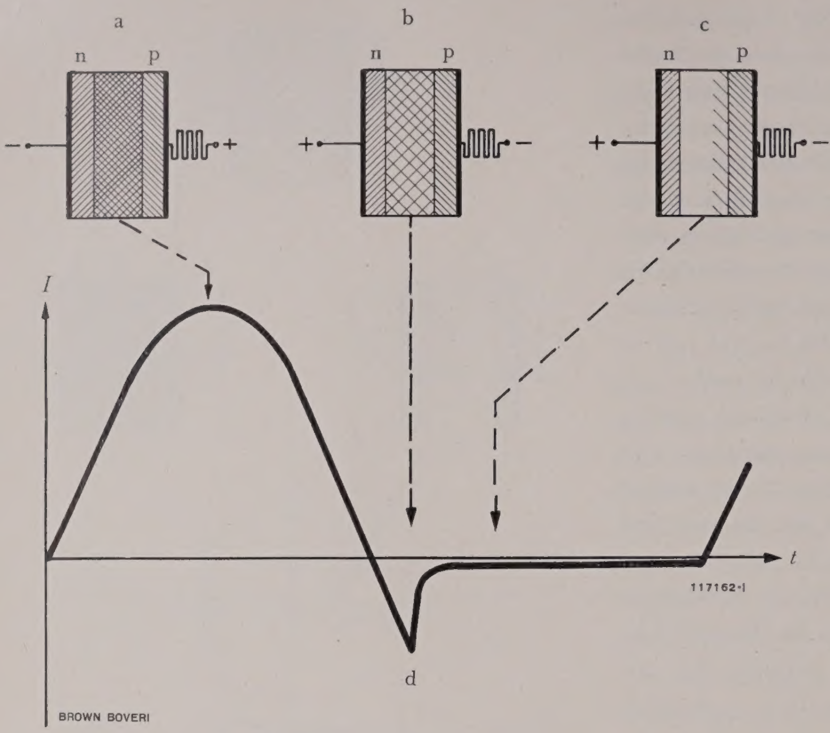

Fig. 3. – Principle of the "hole storage" effect on application of an alternating voltage of high frequency

a: Diode in the forward direction

b: Moment just after voltage zero of the a.c. supply. The charge carriers have all not been discharged yet

c: Diode in the blocking direction

d: Curve of current I in terms of time t

The shading denotes:
= Electrons
= Holes

enriched with carriers during the forward phase. The transition from the conducting to the blocking state, or in other words, the reduction of the high carrier density in this zone (s zone), is subject to a certain inertia, the extent of which is governed by two processes. On the one hand the over-increase in the density inside the semiconductor is diminished by a recombination of the electrons and holes; on the other hand these are discharged via an external circuit, in the manner of a capacitor. As regards the operational behaviour this implies that when the change from the inverse to the forward phase occurs very rapidly, i.e. at high operating frequencies, or when commuting polyphase circuits, an elevated inverse current may flow for a certain time (see Fig. 3). This is what is known as the carrier storage (or predominant in the literature "hole storage") effect. This inertia effect is typical of all elements with pn junctions. The abrupt cut-off of the current (cf. Fig. 3d) results in high voltage peaks being produced at the inductances of the external circuit which, being additional to the inverse voltage, can represent quite a serious hazard for the diode. However, these overvoltages can be reduced to a harmless level by taking suitable precautions.

Following these general remarks on the mechanism of the rectification process and the functional construction of a rectifier element, let us now examine how these principles are put into practice.

By means of a thermal process, a pn junction is produced on one side of a silicon wafer in close contact with the doping material, and a non-blocking, low-resistance zone on the other side. This is illustrated in Fig. 4 showing the schematic arrangement of a power rectifier element. The densely shaded areas denote the highly doped zones of the silicon wafer. The pn junction is in the upper part and comes to the surface at the point marked pn. The current flows through a lead of flexible stranded wire K with the end-piece E, joined to the semiconductor wafer by the solder L_1. In order to match the coefficients of thermal expansion, the wafer is soldered (L_2) to a supporting plate T and the latter (with L_3) to the underpart of the body.

In addition to carrying the current with the minimum of losses, the task of the latter joint with the body is to dissipate the heat generated in the semiconductor. It was stated earlier that the inverse current increases exponentially with the temperature, so that if insufficient provision were made for dis-

posing of the waste heat, the element would be destroyed in next to no time by the rapidly increasing blocking losses. For example, in a rectifier element rated at a mean forward current of 200 A, an average of 240 W is produced in a volume of only about 2×10^{-2} cm³. Working this out a figure of 12 kW/cm³ of waste heat is obtained, and must be dissipated. In the silicon rectifier, in contrast, the blocking losses can be practically ignored because they amount to less than 1 % of the above figure in the forward direction, provided the temperature in the blocking layer is kept below 140 °C; this figure refers to rated voltage. On account of this high temperature permissible in the blocking layer, it is possible to employ air cooling throughout for dissipation of the waste heat of the silicon rectifier. Compared with other methods of cooling, this system is noteworthy for its simplicity and reliability. The diode is screwed into a cooling attachment (Fig. 6b) provided with a number of fins to increase the area of the cooling surface exposed to the current of air.

With germanium elements the conditions are rather less favourable. Since the inverse currents are a good deal higher than with silicon, the blocking losses are comparable with the forward losses at quite a low temperature, e.g. 80 °C. In contrast to silicon, the high blocking current limits the maximum usable inverse voltage of the germanium rectifier to between 200 and 300 V, even though the element may be tested at 600 V or more. These are the main reasons why Brown Boveri decided to concentrate the whole of their attention to silicon diodes, although excellent results have been obtained in service with germanium rectifiers.

The foregoing remarks were only based on the operating principle of a rectifier element. For the practical manufacture of a diode and its optimum functional performance, however, certain conditions must be fulfilled, which will now be briefly mentioned. One concerns the crystal material, which must firstly possess the high resistance necessary for a rectifier with a high inverse voltage; on the other hand, good forward and blocking properties demand considerable freedom from any kind of impurity, even those which only exert an insignificant influence on the specific resistance of the crystal.

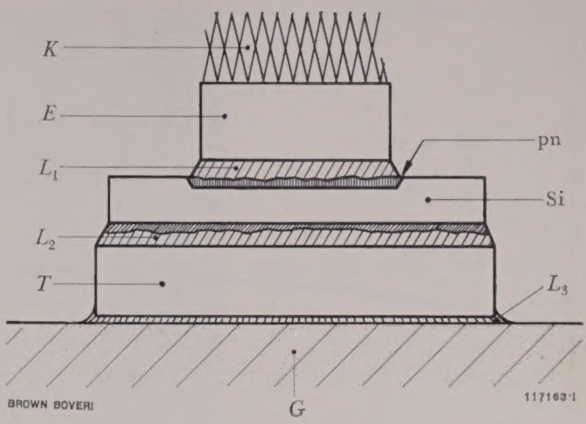

Fig. 4.—Schematic section through a silicon power rectifier element

K = Flexible supply lead
E = End-piece making connection with electrode
L_1, L_2, L_3 = Soldered joints
T = Supporting plate
G = Base
pn = Point at which the pn junction surfaces
Si = Silicon wafer
||||| = Highly doped boundary zones of the Si wafer

As regards the attainable inverse voltage other decisive factors, apart from the crystal material and perfect pn junctions, are the nature of the surface of the crystal, in particular in the vicinity of the point where the pn junction comes to the surface. The high field strengths already mentioned of over 100 kV/cm in service demand maximum possible purity—constant with respect to time—of this surface, especially when due regard is paid to the requirement of low blocking current. This surface quality is obtained by an etching process combined with oxydization to stabilize the state of the surface, thereby ensuring that the good blocking qualities are permanently retained.

The Brown Boveri High-Power Diode DS 200

The object of the development programme carried out by Brown Boveri was to develop a diode with a mean d.c. figure of 200 A and a rated inverse voltage in operation of 600 V. This rated voltage necessitates an inverse voltage of 1000 V at least in order to be able to cope with the overvoltages occurring during operation. Following systematic development work,

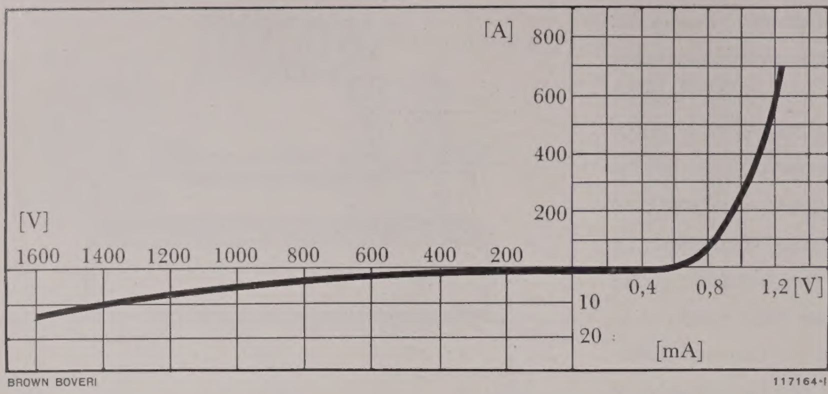

Fig. 5. – Current-voltage characteristic of the DS 200 diode

The curve shows the average values for 1000 elements in the course of a normal production batch. Note the different scales for the currents and voltages in the inverse and forward directions.

and with extreme cleanliness in manufacture, it has proved possible to increase the test voltage from 1000 to over 1200 V, i.e. more than twice the rated inverse voltage, thus affording maximum reliability. The current-voltage characteristic of the DS 200 power diode can be seen in Fig. 5, which represents the average curve for a production batch of 1000 diodes.

In addition to the conditions mentioned in the previous chapter, which must be fulfilled if high-quality diodes are to be obtained, a primary factor for the constancy of the parameters and indeed for the entire performance is the design of the enclosure. Apart from assuring good heat transfer to the cooling system, the body must be perfectly sealed, mechanically robust and possess a high electric strength. This was achieved by employing as insulation the Kovar hard-glass seal normally used in the manufacture of electron tubes. By employing only silver solder for all soldered joints in the body, not only is a perfect seal obtained, it is also possible to use a terminal bolt instead of the direct connection with the flexible lead. The choice of external lead is then free and can be made to suit the requirements of a particular installation. The diode DS 200 is shown with and without its cooling attachment in Fig. 6, while Fig. 7 shows it in its plastic foam packing.

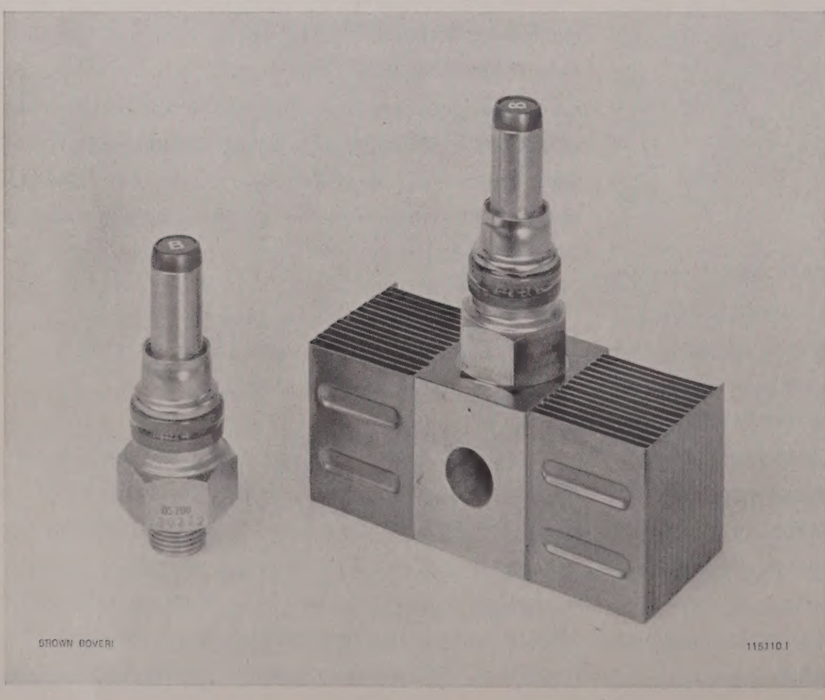

Fig. 6. – The Brown Boveri silicon diode DS 200 for a mean direct current of 200 A and a normal inverse voltage of 600 V

a: Without cooling attachment
b: With cooling attachment

Fig. 7. – The DS 200 diode in its plastic foam packing

Testing the DS 200 Diode

Whether and to what extent a diode complies with the stipulated conditions is determined when it is tested. The tests can be subdivided into three categories:

1. Observation of the blocking properties with regard to the maximum attainable inverse voltage and inverse current. This affords the main criterion for the quality of the pn junction and the surface treatment.
2. Examination of the behaviour of the inverse current on load. This implies the change—mainly the increase—in the inverse current with rising load. This test is particularly valuable because it provides information regarding the soldered joints and the service behaviour of the diode.
3. Determination of the precise forward voltage drop at the peak current of 600 A, enabling the element to be classified with respect to its possible future use in a parallel connection. By this means the current capacity of diodes can be rationally utilized in an installation.

The true object of testing is not to eliminate those diodes which exhibit mechanical or electrical defects, but to gain as much information as possible about its future behaviour in operation. The observation of a large number of rectifier elements undergoing endurance tests can only be undertaken at quite heavy expense, because at a corresponding overload, an output power of over 100 kW must be reckoned with per diode. For this reason the load test is augmented by an impulse test in the course of which the diode is thermally stressed to the ultimate limit. As this is dealt with in a subsequent article,[3] it will not be dwelt upon further here.

The high test voltage of over 1200 V to which the DS 200 diode is subjected, its surface protection and enclosure, combined with the severe tests, ensure that semiconductor rectifier installations are able to completely fulfil the expectations made with regard to robustness and long life, in conjunction with high efficiency.

(KME) E. WEISSHAAR

[3] See the article on page 244.

OPERATION AND PROTECTION OF SILICON DIODES

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This article explains those operational properties and techniques adopted when planning the protection of silicon rectifier installations. The combinations of protective devices employed, the most important of which are fuses, shorting switches, d.c. circuit-breakers and a.c. circuit-breakers, are compared and the conditions listed, under which their respective use is recommended.

SILICON RECTIFIERS possess a number of excellent operational properties, the most important of which are their high efficiency, reliability, easy maintenance, and the small number of spare parts which have to be stocked. These are offset by the limited overload capacity and the sensitivity to brief overvoltage peaks. Hence the silicon rectifier has to be dimensioned to withstand the maximum load surge likely to occur in service and protected against short circuits by quick-acting switchgear adapted to the load capacity of the diodes. From the voltage aspect the rectifier should be amply dimensioned, overvoltages being limited by suitable protective devices and switchgear.

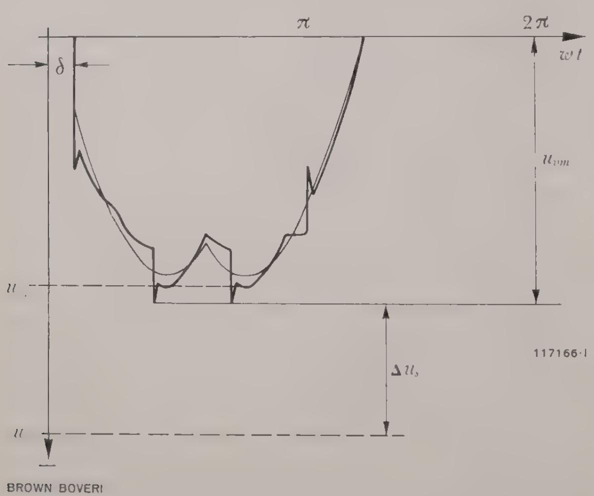

Fig. 1. – Curve of the inverse voltage of a diode in three-phase bridge connection

The thin line represents the curve of the periodically recurring sinusoidal inverse voltage. The heavy line takes into account the voltage harmonics and peaks caused by the hole-storage effect.

u_{v1} = Rated value
u_{vs} = Limit for admissible short-time, non-recurring inverse voltage peaks
Δu_s = Voltage reserve for switching overvoltages
u_{vm} = Maximum periodically recurring inverse voltage
δ = Overlap
ω = Angular frequency
t = Time

1. Inverse Voltages of a Silicon Diode in Service

Fig. 1 shows the typical curve of the inverse voltage experienced by a silicon diode in service when connected, for instance, in a three-phase bridge circuit. The periodically recurring peak value of the sinusoidal inverse voltage, including fluctuations of the mains voltage and harmonics, which ought not to amount to more than 5 % of the peak value, must not exceed the rated inverse voltage of the diode. For the DS 200 diode, for instance, this value is 600 V. All voltages occurring in service, including the peaks caused by the hole-storage effect and switching surges, should be well below the test voltage of the particular diode.

2. Forward Properties of the Silicon Diode

The behaviour of the diode in the forward direction is governed by the forward characteristic, as shown in Fig. 2. This characteristic can be approximately represented in the operating range by two straight lines, the positions of which are determined by the threshold voltage U_{th} and the differential resistance R_{ac}, also known as the path resistance.

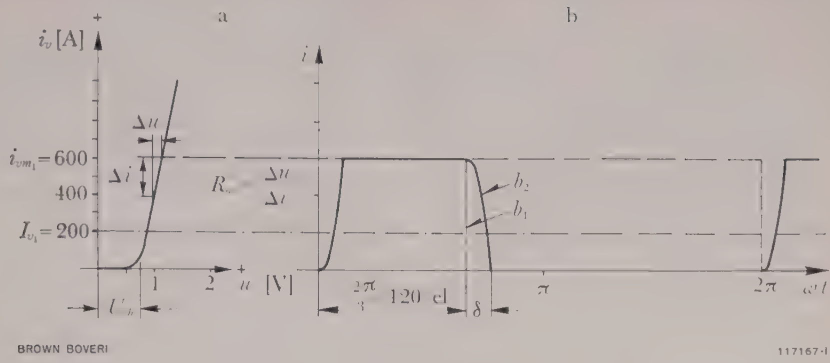

Fig. 2. – Behaviour of the diode DS 200 in the forward direction

a: Forward characteristic of the diode DS 200

U_{th} = Threshold voltage
R_{ac} = Differential (path) resistance
i_v = Momentary value of diode current
u_v = Momentary value of diode voltage

I_{v1} = Rated diode current = Mean value with illustrated form of the current
i_{vm1} = Peak value of rated current
ω = Angular frequency
t = Time

b: Diode current when connected in three-phase bridge or double-star circuit with interphase transformer
b_1 = Current without overlap (conducting for 120° el. per cycle)
b_2 = Current with overlap δ

With these quantities the voltage drop in the diode can be expressed by the following equation:

$$u_v = U_{th} + R_{ac} \cdot i_v \qquad (1)$$

in which u_v and i_v are the momentary values of the diode voltage and current. The forward loss power is then given by:

$$P_v = \frac{1}{T} \int_0^T u_v \cdot i_v \, \mathrm{d}t = U_{th} I_{dv} + R_{ac} I_v^2 \qquad (2)$$

where T = duration of the cycle
I_{dv} = mean value of diode current
I_v = effective value of the diode current

From equation (2) it is evident that the forward losses depend on the mean and effective values of the diode current. When operating at rated conditions they are determined mainly by the mean value, whereas under surge load conditions the governing factor is the effective value. In practice only the forward losses need to be considered, since the inverse losses represent only a very small percentage.

The diode current of a rectifier in three-phase bridge connection, loaded with a rated direct current of I_{d1} = 600 A has a

mean value of $I_{dv1} = I_{d1}/3 = 200$ A and an
effective value of $I_{v1} = I_{d1}/\sqrt{3} = 347$ A;

from which it follows, according to equation (2), that the forward loss power at this load is

$$P_v = 230 \text{ W}$$

The inverse losses amount to less than 10 W, so that the total losses at rated load are

$$P_{v1} = 230 + 10 = 240 \text{ W}$$

The rated current is determined by the diode losses; it is such that, when the diode is carrying the rated current, the silicon wafer does not rise above a certain admissible temperature—with given ventilation conditions—if the ambient temperature has attained the admissible limit.

Fig. 2 b shows the curve of the diode current of an inductively loaded rectifier connected as a three-phase bridge or in double-star connection with interphase transformer. The rated figure was determined for these two connections. It is the mean current for a rectangular wave-form and a flow duration of 120 ° per cycle; for the DS 200 diode it is 200 A, the peak value being 600 A. The influence of overlap on the forward losses can be neglected to all intents and purposes.

3. Parallel and Series Connection of Silicon Diodes

a. Parallel connection

The connection of diodes in parallel is often used for heavy-current rectifiers, because these rectifiers can then be constructed from only one type of diode,

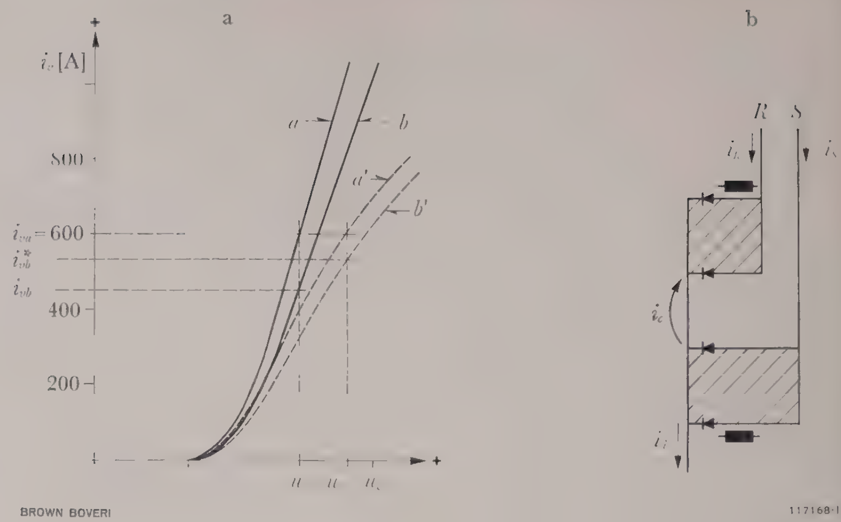

Fig. 3. – Parallel connection of silicon diodes

a: Current divided between two parallel diodes having different forward characteristics
——— = Current-voltage characteristics of the diodes
- - - - = Current-voltage characteristics of the diodes and fuses
i_v = Diode current
i_{va} = Current of diode *a* with or without fuse
i_{vb} = Current of diode *b* without fuse
i^*_{vb} = Current of diode *b* with fuse
u_v = Voltage drop of diode
u^*_v = Voltage drop of diode and fuse

b: Loops in the commutation circuit of parallel diodes
▨ = Additional loop area effecting an increase in the inductance
i_c = Commutation current
i_d = Direct current
i_R = Current in a.c. lead, phase *R*
i_S = Current in a.c. lead, phase *S*

even for very high outputs. The greatest problem with parallel diodes is to distribute the current as uniformly as possible between all the diodes, in order that their individual losses do not exceed the permissible figure. This is only feasible to a certain extent, owing to the slight, but inevitable differences between the individual forward characteristics of the diodes. Fig. 3a, for example, shows how the current may be divided between a pair of parallel diodes, whose characteristics are at the boundaries of the tolerances. Whereas one diode can be operated at rated current with the indicated voltage drop, the current of the second is 25 % lower. Consequently the total current in the rectifier limb, in continuous operation, is only 175 % of the rated diode current.

A slight, but nevertheless unfavourable effect on the current distribution is exerted by the negative temperature coefficient of the diode. If fuses are employed to protect the diodes, their voltage drop, particularly at heavy currents, tends to balance the effect of the current because their resistance rapidly increases with current, owing to the heating of the fuse-wire (Fig. 3a).

When diodes or groups of diodes are operated in parallel, every effort is made to keep the inductances of the conductor loops in the commutating circuits as nearly equal as possible, because large differences can adversely affect the current distribution (Fig. 3b).

b. Series connection

In traction service, rectifiers are required for voltages of 600 to 3000 V. With silicon elements, these high service voltages can only be attained when the diodes are connected in series. Fig. 4 shows a number of different circuits, Fig. 4a the series connection of a pair of diodes. It is preferable to connect capacitors and resistance voltage dividers in parallel with the diodes or groups of diodes. The main task of the capacitors is to ensure uniform voltage distribution. They are needed because the various diodes reach their full blocking capacity at different moments, their blocking time-lags being different. Without provision of a parallel capacitor the first diode to block would have to withstand the full inverse voltage. The parallel capacitor prevents an abrupt rise in the voltage of the first diode to block, ensuring that the charge carriers flow more rapidly away from the

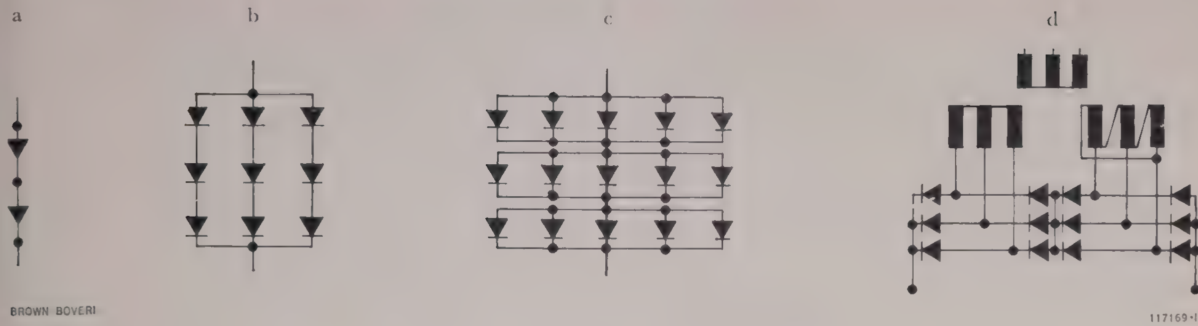

Fig. 4. – Series connection of silicon diodes

a: Two diodes in series

b: Series groups of diodes connected in parallel

c: Parallel groups of diodes connected in series

d: Two three-phase bridges in series, producing a twelve-pulse output

blocking layers of the other diodes, enabling them to achieve their blocking capacity in a very short time. Thus the inverse voltage is evenly divided between the series diodes or groups during the whole of the inverse period.

When groups of series diodes are connected in parallel as in Fig. 4b, a good current distribution is obtained and a faulty group can be disconnected selectively by means of a fuse. The series connection of parallel groups in Fig. 4c ensures good voltage distribution. The advantage of this circuit arrangement is that signalling in the event of a fault is quite easily effected; it suffers from the disadvantage, though, that a fault in one diode automatically renders the others in its group inoperative. Fig. 4d shows the series connection of two three-phase bridges to produce a twelve-pulse output. Each part of the rectifier can be treated as a separate entity and dealt with as if it were a simple circuit.

4. Overload Properties of the Silicon Diode

To accurately describe the overload behaviour of the diode is a relatively complicated matter, because the temperatures are unevenly distributed across the silicon wafer, the means of holding and the cooling attachment. The behaviour can, however, be easily explained with a simplified thermal diagram, as shown in Fig. 5a [1, 2].[1] According to this the diode is split into four heat storage elements, each of which absorbs part of the heat generated and accordingly becomes warm. These storage elements are connected with one another by thermal resistors, on the passage of heat through which a drop in temperature occurs. Store I is the silicon wafer, having a small heat capacity. The unwanted heat is generated in it. This heat is first absorbed by the wafer, which rapidly becomes hot compared with the means of holding it. The temperature rises according to the transfer function $(1-e^{t/T})$, reaching its ultimate value in about 1 ms, as determined by the thermal resistances and the power to be dissipated. As the temperature rises, an increased proportion of the heat is given up to the holder through the thermal resistance, and conducted through the holder. The latter is represented by the two storage elements II and III, having a larger heat capacity than the silicon wafer and a total time constant of the order of 100–200 ms. Finally the heat reaches the cooler (store IV) having a time constant of about 100 s, where it is transferred to the current of air. If the draught is forced through the cooler, the transfer of heat is intensified, the thermal resistance and the time constant being reduced and, as a result, the overload capacity of the diode increased. Air cooling has hardly any influence on the properties at surge load.

The variation of the temperature of the silicon wafer following a sudden increase in the load, i.e. in the heat generated, is illustrated approximately in Fig. 5b and c, giving the final temperature rise and the time constants. From this curve it will be observed that the rise in the temperature of the wafer, compared with that of the holder, follows the change

[1] The figures in square brackets refer to the bibliography at the end of the article.

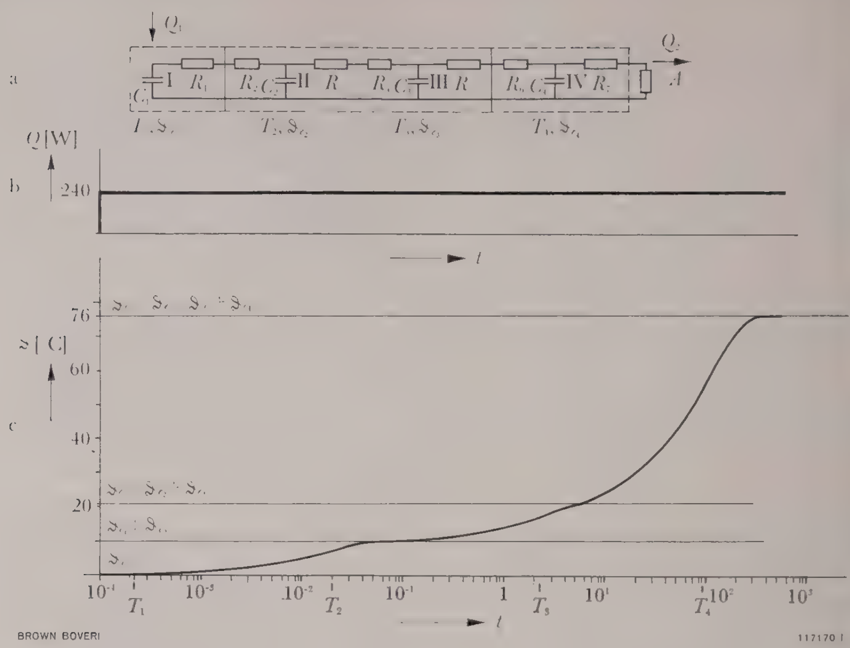

Fig. 5. – Overload properties of silicon diodes

a: Simplified thermal diagram of a silicon diode, showing heat stores

I = Silicon wafer
II, III = Holder
IV = Cooling attachment
C_1–C_4 = Heat storage capacity in Ws/°C
R_1–R_7 = Thermal resistance in °C/W
Q_1 = Flow of waste heat in the silicon wafer in W
Q_2 = Heat dissipated by the cooler in W
A = Ambient air

b: Abrupt change in load (i.e. heat generated) $Q = Q_1$ in W

c: Temperature of the silicon wafer following an abrupt increase in load and heat generated

ϑ = Temperature rise of silicon wafer relative to ambient in °C
ϑ_{e1} = Final temperature rise between silicon wafer and holder
$\vartheta_{e2} + \vartheta_{e3}$ = Final temperature rise between holder and cooling attachment
ϑ_{e4} = Final temperature rise between cooler and ambient air
T_1–T_4 = Time constants in s
t = Time

in the heat generated, with only a short time-lag. The rise in temperature of the holder relative to the cooler assumes a level roughly equivalent to the average power dissipation after a few cycles and the temperatures of the cooling attachment follows slow changes in load. Assuming, for instance, that a diode is loaded for 10 s with a constant surge of four times the rated load, the average value of the heat generated is given by

$$P_v = U_{th} \cdot 4 I_{dv1} + R_{ac} \cdot (4 I_{dv1})^2 = 1030 \text{ W}$$

or, referred to the losses under normal circumstances,

$$\frac{P_v}{P_{v1}} = \frac{1030}{240} = 4{\cdot}3$$

The rise in the temperature of the silicon wafer after this load surge depends on the time and can be determined from Fig. 5c by multiplying the value obtained from the temperature rise curve by the factor 4·3. Following a load period of 1 ms the temperature rise works out to about 4·3 °C, after 0·1 s about 43 °C, and after 10 s about 103 °C.

For both rated and surge load conditions there is a limit which the temperature of the silicon must not exceed. The difference between the two values is visualized for the additional temperature rise of the silicon wafer in the event of a short circuit. The sudden rise in the heat generated until a short circuit is interrupted has to be absorbed almost entirely by the silicon wafer. If the duration of the overload does not greatly exceed the time constant of the silicon, the permissible energy which may be dissipated is a fixed value, given approximately by the integral $\int i^2 \mathrm{d}t$.

For practical conditions the overload characteristic of the silicon diode is given in Fig. 6, in which the current surges are depicted as a function of time, in one case permissible following operation at rated load,

and in the other case following no-load. The current wave-forms are experienced in service and during a short circuit, thus permitting a direct comparison, from which the overload capacity of a rectifier can be quickly determined. From the overload characteristic it is also evident that, when the overload lasts more than a few seconds, the diodes may only be loaded slightly above their rated figure. Therefore, in many cases the rectifier has to be designed for the maximum load surges likely to occur.

5. Stresses Imposed by Disturbances in the Silicon Rectifier Installation

When designing silicon rectifiers, the stresses which might be imposed by possible faults must be given special consideration. The most important cases are therefore dealt with below.

a. Short circuits

In silicon rectifier installations a distinction must be made between "internal" and "external" short circuits. Fig. 7 shows the different possible faults for rectifiers connected as a three-phase bridge, or double-star circuits with interphase transformers. It is customary to refer to an internal short circuit when a diode loses its blocking capacity. As may be seen from Fig. 7a, this kind of fault short-circuits two phases of the transformer. The healthy rectifier limb, which is still carrying current, feeds the affected limbs; a short-circuit current rapidly rises and may reach the admissible limit in only a few ms, depending on the arrangement of the transformer and rectifier. On the other hand, an internal short circuit as in Fig. 7a does not represent a short on the d.c. side because there are two diodes in series. In contrast, with the double-star connection with interphase transformers (Fig. 7b), parallel connected rectifiers or load circuits can feed into the fault point if they possess a back-e.m.f.

Short circuits on the d.c. side (see Fig. 7c) are referred to as external. If a short circuit occurs at the d.c. terminals, the current can rise within a few ms to an inadmissible height. When the short circuit is on the d.c. leads, the form of the short-circuit current is governed by the distance between the fault point and

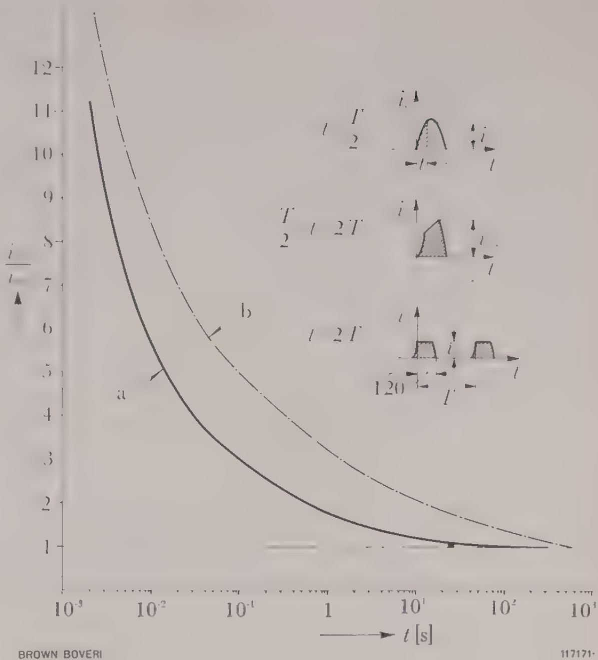

Fig. 6. – Overload characteristic of the silicon diode

The ratio of the peak surge current i_{vm} to the rated diode current i_{vm_1} is plotted against time, after rated load (a) and after no-load (b).

T = Duration of 1 cycle (20 ms)
t = Duration of overload
i_v = Diode current

the rectifier, and by the electrical data of the leads. The rise in current is only retarded by the inductance of the leads, the final value of the short-circuit current being determined by the inductive voltage drop of the rectifier and the ohmic resistance of the short circuit.

b. Overload

Rectifiers for fluctuating loads are dimensioned according to the overload characteristic for the maximum load surge. If the normal service load limit is exceeded, the protective gear switches off the rectifier.

c. Overvoltage

In all semiconductor rectifier installations it is important to limit overvoltages, in order to prevent the diodes from being damaged. The various causes are as follows.

Overvoltages may be produced by the "hole-storage" effect. They are reduced to harmless, low values by well-known means.

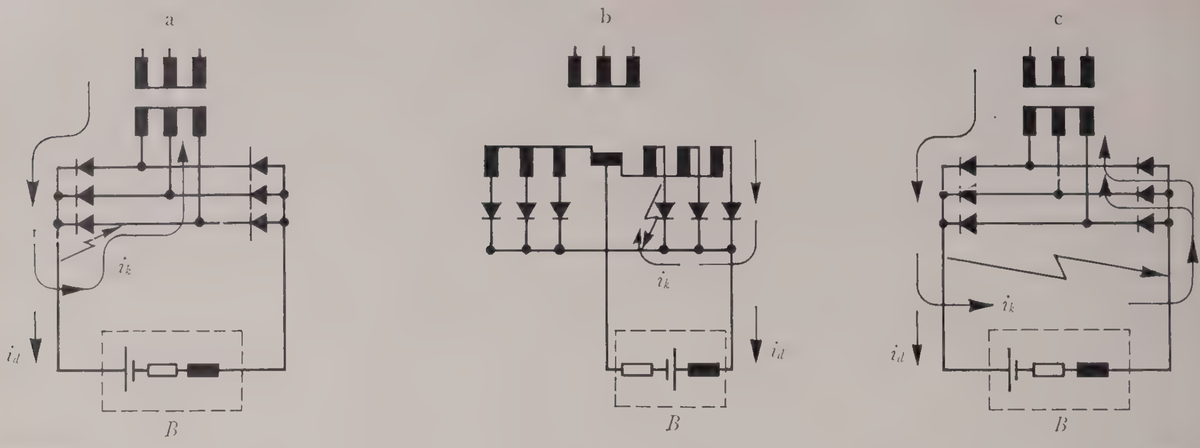

Fig. 7. – Different forms of short circuits in rectifiers

a: Internal short circuit when connected as three-phase bridge
b: Internal short circuit when connected in double star with interphase transformer
c: External short circuit

i_d = Direct current in service
i_k = Short-circuit current
⌇ = Short circuit
B = Load

When short circuits are interrupted by fuses, overvoltages can be produced which depend on the magnitude of the arc voltage and the circuitry. In most cases fuses are used which have a defined, low arc voltage.

Transient overvoltages occurring when a d.c. breaker is opened, or a fuse on the d.c. side blows, are dealt with in section 8.

If the unloaded rectifier is disconnected on the a.c. side, some of the magnetic energy stored in the transformer is converted into electrostatic energy of the winding and lead capacitances. Since the latter are often very small, high overvoltages can be produced on interruption, but they can be limited by suitable protective devices (see section 11).

Overvoltages produced when the rectifier is switched on can be transferred to the secondary side through the winding capacitance. Their influence on the diodes is slight if low-inductance capacitors are connected in parallel with the valves.

Switching overvoltages can be transmitted by the three-phase supply system to the rectifier; these may be produced, for instance, when capacitors, inductances or series transformers at no-load are disconnected, or when circuits capable of resonance are closed. Operational experience so far gained with silicon rectifiers has shown that the voltage reserve mentioned in section 1 is quite adequate. If adverse conditions are known to exist, these can be taken into account in the design stage [3].

Overvoltages of atmospheric origin only need to be taken into account when the rectifier transformer is connected to a high-voltage transmission line. In such cases lightning arresters and an earth-wire must be provided on the h.v. side, and the masts must be adequately earthed.

6. Protection of Diodes by Fuses

Fuses are often used to protect silicon diodes, either to selectively disconnect defective diodes in the event of an internal fault—as is usually the case with high-power rectifiers having a large number of diodes—or to protect the diodes against external short circuits on the d.c. side. The latter is often stipulated for low-power rectifiers.

The effect of protection by fuses in the event of internal short circuits can be seen from the circuit diagram in Fig. 8a and the oscillograms in Fig. 9. The rectifier in Fig. 8a has three parallel diodes per limb. If one diode ceases to block, two phases of the transformer are short-circuited; the rectifier limb which is just conducting feeds into the short circuit. Whereas the current rises very rapidly in the affected

a: Diode fuses, internal short circuit

b: Diode fuses, external short circuit

c: Feeder fuses, internal short circuit, one diode per rectifier limb

d: Feeder fuses, external short circuit

e: Feeder fuses, internal short circuit, rectifier with parallel limbs

f: Fuse in d.c. circuit, external short circuit

i_d = Service direct current

i_k = Short-circuit current

= Fuse

B = Load

L_v = Inductance on anode side

L_d = Inductance of d.c. line, or a d.c. choke

+, − = Polarity of the arc voltage of the fuse, the transient voltage at the inductances and the diode overvoltage. Lower overvoltages are possible at the diodes marked (+ −)

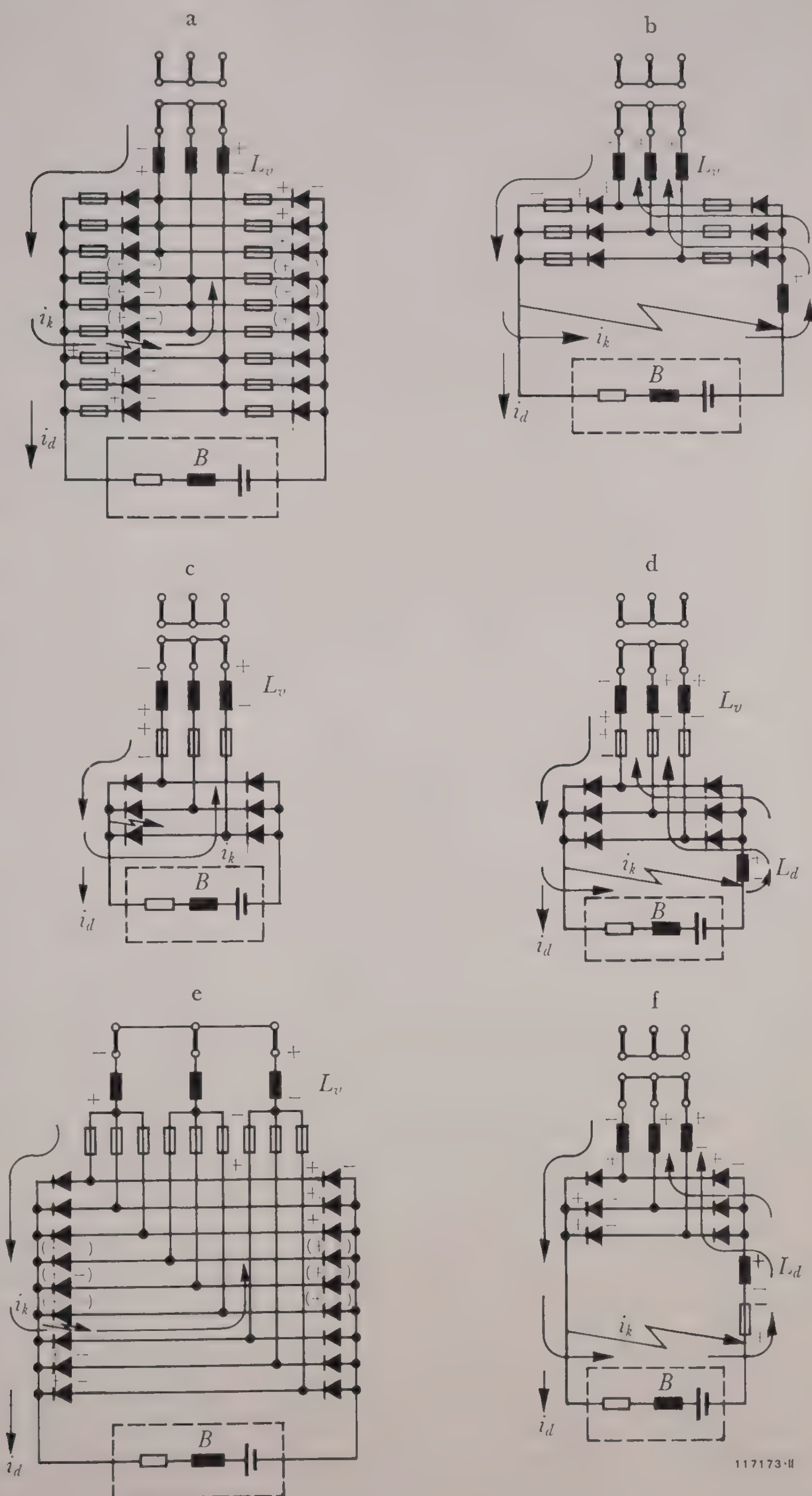

Fig. 8. – Silicon rectifier in three-phase bridge with protection by fuses

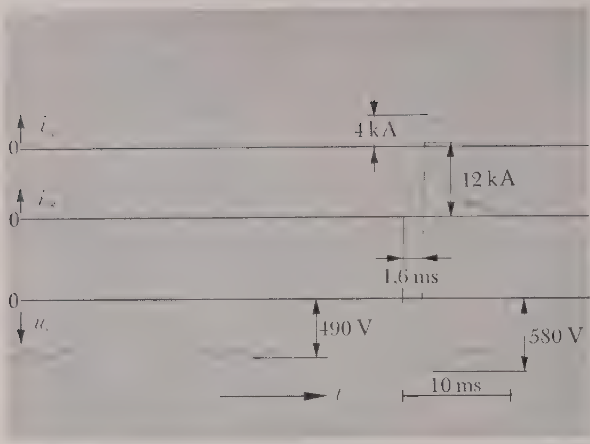

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Fig. 9. – Oscillograms of voltage and current during an internal short circuit with interruption by a fuse

i_{vp} = Current in a diode of the healthy rectifier limb with three parallel diodes feeding into the short circuit
i_{vk} = Short-circuit current in the defective diode limb
u_v = Inverse voltage at the healthy diodes of the affected limb
t = Time

diode lead, it is uniformly distributed between the three parallel diodes of the healthy limb. This may be seen in the oscillogram in Fig. 9. The work of fusion of the fuse, as expressed by $\int i^2 \mathrm{d}t$ is the factor which decides how many diodes must be connected in parallel so that, in the event of a fault, the healthy, conducting diodes are certain not to be overloaded. The faulty diode is selectively disconnected by the associated fuse, without interrupting the operation of the rectifier.

Following the melting of the fuse-wire, an arc is produced, the voltage across which demands close attention. As may be seen from Fig. 8a, the healthy diodes in the affected limb, and also the diodes in the other limbs, can be stressed by the arc voltage in their inverse direction. This voltage is therefore limited to a tolerable value, as may be seen in Fig. 9, in which the inverse voltage is also shown. The curve contains the different stages: normal operation, the collapse of the voltage at the instant the short circuit occurs until the fuse melts, and then the rise up to the arc voltage of the fuse. The latter must be higher than the service voltage in order that the magnetic energy stored in the stray inductances of the transformer during the short circuit is dissipated and the short-circuit current rapidly reduced.

In order that the additional temperature rise of the silicon wafer may be small on the occurrence of a fault, ultra-rapid fuses are used. They are ideal for overload protection because the melting characteristic of the fuse almost coincides with the overload characteristic of the diode. This is particularly true for short melting times at heavy short-circuit currents, because then the diode losses and the heat of fusion of the fuse are both largely dependent upon the effective value of the current, but to a lesser extent when the overload is of long duration. Generally speaking, it is sufficient for the fuse characteristic to match that of the diode up to a few tenths of a second, in which space of time the diode is protected by the fuse.

Fig. 8 shows various arrangements which may be used for the fuses. The currents are denoted by i_d for normal operation and i_k for short-circuit conditions, and the overvoltages at the diodes are marked + and –. The inductances on the cathode and anode sides are also indicated [4].

When connected as in circuits 8a and 8b, each diode is protected by its own fuse. The fuses are designed to carry the effective current of the diode. The fuse rating in this case is lower than for other circuit arrangements with the same diode current. Hence fuses with a lower current rating can be used, having a lower work of fusion and affording better protection for the diodes. When the fuse-wire has melted, the healthy diodes which are in parallel with the defective one, or which are situated in the other marked limbs, may be stressed in the inverse direction with the full arc voltage, or a part of it. In the event of a short circuit on the d.c. side, the overvoltage at the diodes decreases, the larger the inductance of the lines on the d.c. side.

In the circuits 8c and 8d the fuses are in the a.c. leads. The fuse rating in this case is $\sqrt{2}$ times greater than the diode current (both effective values). If a fuse with a higher rating is used, the work of fusion will be greater and the protection against overload less.

Fig. 10. – Ultra-rapid fuse with limitation of the arc voltage, for protection of silicon rectifiers

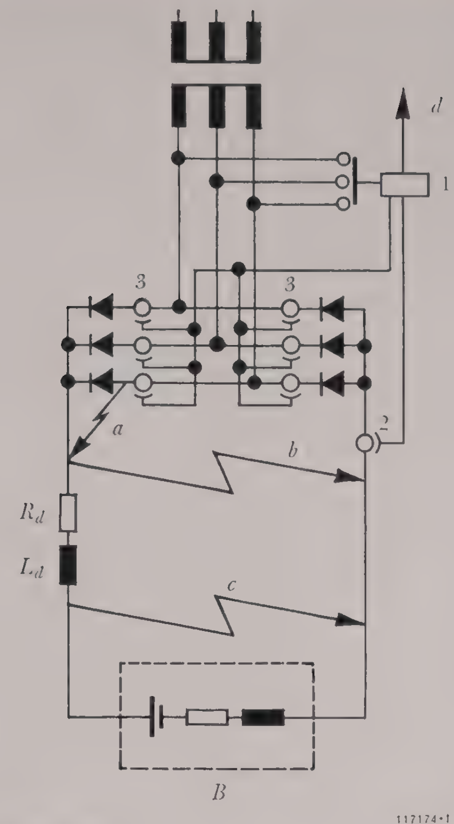

Fig. 11. – Connection of a rectifier with shorting switch

1 = Shorting switch, closure of which imparts a tripping command to the primary breaker
2 = Current transformer in the d.c. circuit for tripping when an external short occurs
3 = Pulse-type reverse-current transformer in the rectifier limbs for tripping when an internal short circuit occurs

B = Load
L_d = Line inductance
R_d = Line resistance
⚡ = Short circuit
a = Internal short circuit
b = Terminal short circuit
c = Line short circuit
d = To the primary breaker

Conditions become still less favourable when only two feeder fuses are used, or if the fuses are in the leads from a delta-connected transformer.

The advantage of connecting the fuses in the a.c. leads is that the arc voltage does not produce any harmful overvoltages at the diodes, because the arc is fed from the alternating voltage and the stray inductances of the transformer, without the voltage rising between the a.c. terminals of the rectifier. This is no longer true when, as in Fig. 8e, several diodes are in parallel. The overvoltages occurring at the diodes are shown for the case in which an internal short circuit is interrupted by one fuse.

Fuses are also occasionally used to protect load circuits, in which case they are connected in the d.c. line (Fig. 8f). The same conditions are then encountered as with the d.c. breaker described in chapter 8. When the load is mainly inductive, fuses should not be used.

As a result of collaboration between Brown Boveri and Schurter AG., Lucerne, a fuse has been developed for the protection of silicon rectifier installations, which interrupts short-circuit currents in a very short time, possesses a low arc voltage adapted to that of the diode, in addition to which it is notable for its small size, matching that of the diode cooling attachment, and its low losses. The connecting lugs allow it to be firmly installed with low contact losses, yet render it easily renewable after a fault. The fuse is illustrated in Fig. 10.

For rectifiers of high outputs it would be undesirable for a large number of fuses to blow every time an external short circuit occurred, thereby requiring replacement. For such rectifiers it is therefore more usual to employ additional shorting switches or d.c. circuit-breakers.

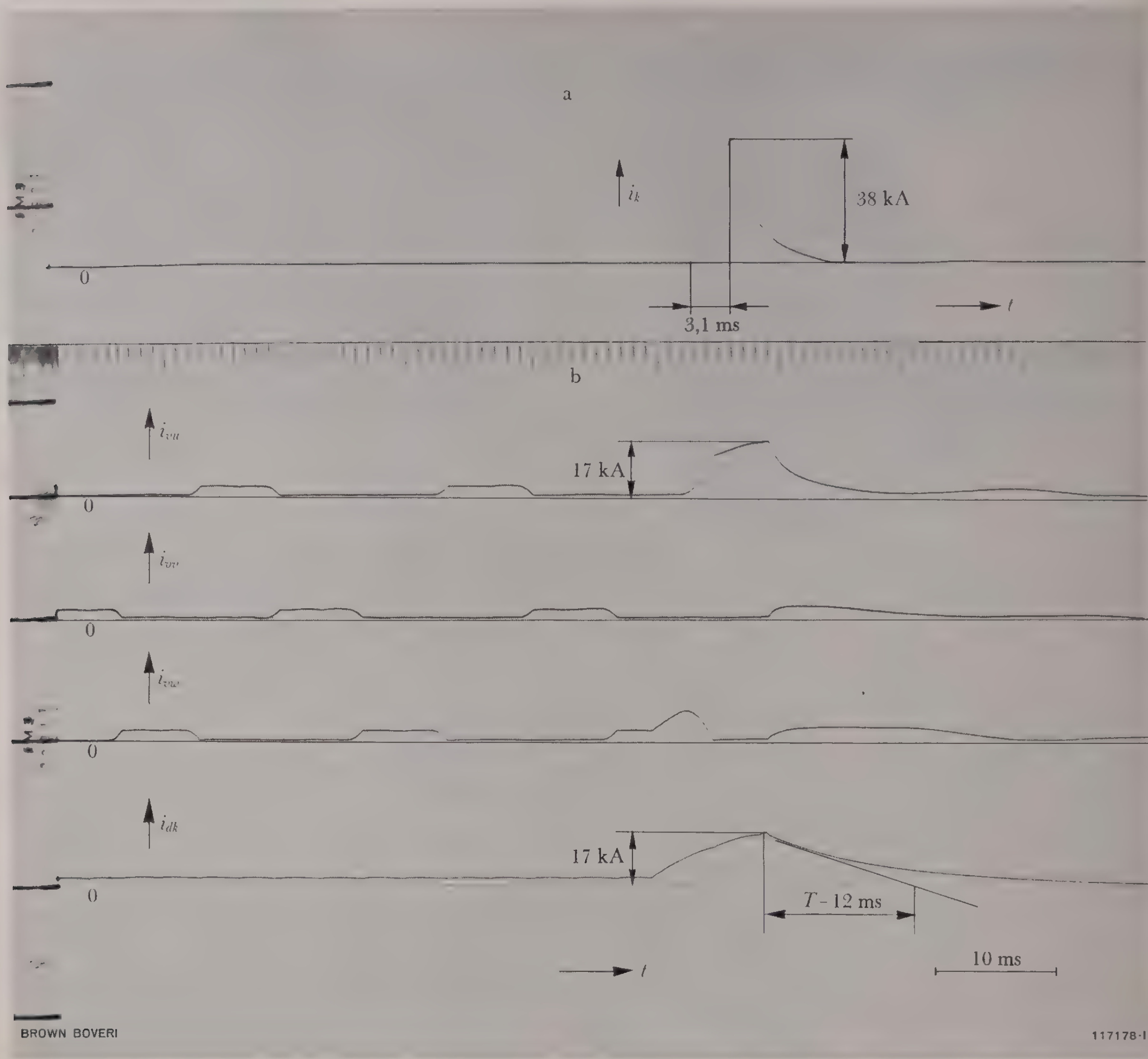

Fig. 12. – Oscillograms of the short-circuit current during internal and external shorts, and on interruption with a shorting switch

a: Short-circuit current i_k in the rectifier limb during an internal short. The current during a terminal short is roughly the same

b: Line short circuit

i_{vu}, i_{vv}, i_{vw} = Currents in the limbs of phases U, V, W

i_{dk} = Short-circuit current on the d.c. side

T = Electrical time constant of the d.c. line

t = Time

The rise and fall of the current are severely retarded by the line inductance. In order to obtain a clear picture of the current, the shorting switch was tripped by an overcurrent.

7. Protection of Rectifiers by Shorting Switches

The restricted overload capacity of the diodes often prohibits the use of d.c. breakers without special supplementary equipment, such as current-limiting chokes, because the time-lag on interruption is too long, whereas shorting switches act quickly enough. This is one of the main reasons for the frequent employment of shorting switches in silicon rectifier installations [5]. The principle of its operation will be explained with reference to Fig. 11 and 12. Fig. 11 shows a rectifier connected as a three-phase bridge circuit and fitted with a shorting switch. The latter is

actuated by a current transformer as soon as the pick-up current or a given rate of rise of current is exceeded. (See also the article on page 228.)

In some cases overcurrent release is preferable, in others the di/dt release, in which case the command is imparted to the shorting switch immediately the short circuit occurs. The di/dt release is used, for example with the shorting switch, for a dead short across the terminals, whereas line shorts and overloads are interrupted by the d.c. breaker. In the event of a fault, the shorting switch short-circuits the a.c. side of the rectifier within 2–3 ms. The rise in the current during this period is determined by the momentary value of the transformer voltages, the inductances in the anode circuits and, if present, the inductance in the short circuit on the d.c. side. As soon as the shorting switch has closed, the current drops. The rate at which it drops depends on the time constant of the circuit between the switch and the point at which the short circuit occurred. The healthy diodes prevent the short from being fed from the d.c. side. When a dead short occurs across the terminals the short-circuit current in the rectifier limb roughly follows the curve shown in Fig. 12a. In contrast, Fig. 12b shows the current on the d.c. side and in the rectifier limbs when a short circuit occurs on a d.c. line with a fairly long time constant and the current only drops slowly.

The rectifier installations are designed so that the diodes can safely withstand the current surges which follow normal or surge-load conditions, between the occurrence of a short circuit and the instant of interruption. The rectifier transformer has to be designed to withstand short circuits; when the shorting switch closes, a tripping command is immediately imparted to the primary circuit-breaker on the a.c. side, whose task is to interrupt the short circuit as rapidly as possible.

Shorting switches are also used sometimes for rectifiers in bridge connection, to protect the diodes against internal short circuits. As may be seen from Fig. 11, additional reverse-current transformers are connected in the rectifier limbs, which impart a tripping command to the shorting switch as soon as an internal short occurs. An oscillogram of the short-circuit current is reproduced in Fig. 12a.

When a mercury-arc rectifier equipped with a d.c. breaker is operating in parallel with a silicon rectifier with shorting switch, the latter, when interrupting line short circuits, may experience additional load due to the short-circuit current of the mercury-arc rectifier. In the event of a short circuit, the silicon rectifier is relieved of the short-circuit current by the shorting switch. The short-circuit current continues to flow in the mercury-arc rectifier until it is interrupted by the d.c. breaker. At this moment some of the short-circuit current may continue to flow through the shorted a.c. side of the silicon rectifier, owing to the magnetic energy on the d.c. side. But since the semiconductor rectifier must not be overloaded under any circumstances, both rectifiers are equipped with d.c. circuit-breakers in such cases.

8. Protection of Rectifiers by D.C. Circuit-Breakers

To protect rectifiers against short circuits on the d.c. side, d.c. circuit-breakers may be employed, provided the rectifier is amply dimensioned with respect to load surges, and particularly when short circuits are likely to occur frequently in the installation and repeated shorting of the transformer is held to be undesirable. When d.c. breakers are used, special attention must be paid to their time-lag on opening and their arc voltage, because these factors primarily determine the duration of the short circuit and the switching overvoltage at the diodes. To prevent the diodes from being overloaded in the event of a short circuit, either the rate of rise of the short-circuit current must be appreciably reduced by the inductance of the d.c. line, or by the incorporation of a choke, or the short-circuit current must be severely limited by the inductive potential drop of the rectifier installation. A further method is to connect more diodes in parallel.

The curve of the arc voltage, and its magnitude, are characteristic of the d.c. breaker. There are

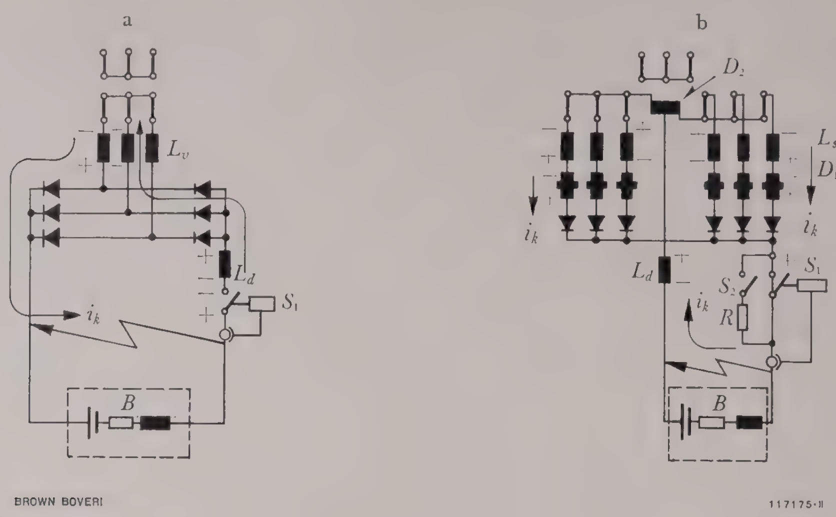

Fig. 13. – Rectifier equipped with a d.c. circuit-breaker

a: Three-phase bridge connection with choke to limit the current rise, and line inductance L_d

b: Double-star connection with
D_1 = Transductor choke and any other inductances on the anode side

D_2 = Interphase transformer
L_d = Choke limiting current rise, and line inductance
L_s = Stray inductance
R = Resistor
S_1 = D.C. circuit-breaker
S_2 = Contactor
⚡ = Short circuit
i_k = Short-circuit current
B = Load
+, – = Polarity of voltage at the breaker and inductances on interruption

breakers equipped with magnetic blow-out for rapid elongation of the arc, in which the arc voltage rises linearly with time; in other models it rises linearly to begin with and then remains roughly constant. A rapid rise of the breaker voltage is desirable, so that the short-circuit current can be limited as soon as the contacts open.

For the current to be interrupted, the breaker voltage must rise above the service voltage. On interruption of a short circuit the arc is fed partly by the rectifier and partly by the inductances of the short circuit; in other cases, e.g. when the service current is interrupted, it is fed almost entirely by the inductances, its voltage being divided in proportion to the inductances on the anode side and the d.c. side (Fig. 13 a). In the double-star circuit with interphase transformer the voltages at the stray inductances of the one transformer secondary can be transmitted to the other secondary winding by the magnetic linkage. The voltages at the inductances on the anode side are added to the service voltages and impose an additional stress on the diodes in the inverse direction. In order to reduce this stress, chokes are sometimes incorporated in the d.c. lines, in other cases the inductance of the d.c. line is large enough on its own, even though the breaker voltage may rise to quite high values. Finally in rectifier installations feeding supply networks, and for parallel-connected silicon rectifiers equipped with shorting switches and d.c. breakers, it is possible for voltages to occur which stress the rectifiers in the inverse direction. The arc voltage of breakers for silicon rectifiers is therefore often limited to twice the value of the rectifier voltage. In any case breakers with a well-defined arc voltage are employed.

The d.c. circuit-breakers can be equipped with either of two methods of tripping, the one responding to overcurrent and the other to the rate of rise of short-circuit current, giving the command to trip the very instant the short circuit starts. A rectifier in three-phase bridge connection, equipped with a d.c. breaker and a current-limiting choke is shown by the diagram in Fig. 13 a. The voltages are

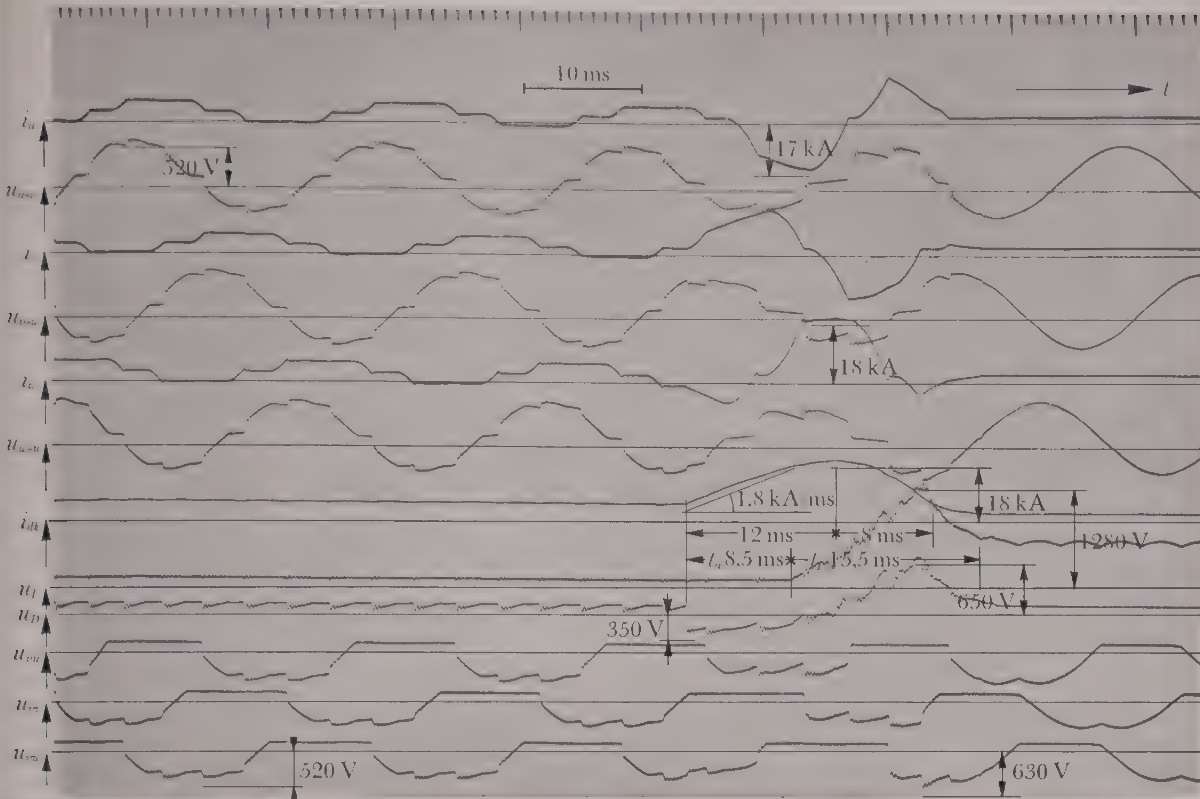

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Fig. 14. – Oscillograms of currents and voltages of a rectifier in three-phase bridge connection during a short circuit on the d.c. side, with interruption by a d.c. circuit-breaker

i_u, i_v, i_w = Currents in the a.c. leads of phases U, V, W. The positive half-wave flows through the forward diodes, the negative through the inversely connected diodes.

u_{u-v}, u_{v-w}, u_{w-u} = Linked secondary voltages of the transformer, between phases U–V, V–W, W–U

i_{dk} = Short-circuit current on the d.c. side

u_L = Breaker voltage (arc voltage)

u_d = Voltage at the choke limiting the short-circuit current, or the line inductance

u_{vu}, u_{vv}, u_{vw} = Inverse voltage at the diodes of the positive pole of phases U, V, W

t_a = Break time of the breaker

t_L = Duration of arc

The rise of the short-circuit current and the switching overvoltages at the diodes are considerably reduced by the inductance of the d.c. line or by the limiting choke.

indicated at the breaker and the inductances for the case in which a dead short across the terminals is interrupted.

The oscillograms in Fig. 14 show the shapes of the short-circuit currents and the voltages. From the occurrence of the short circuit, the direct current i_{dk} rises approximately linearly during the breaker time-lag. The rate of rise is governed by the rectifier voltage and short-circuit inductances. The current drops again as soon as the arc voltage u_L exceeds the rectifier voltage. As regards the load on the diodes, the currents in the rectifier limbs are important; these are denoted by i_u, i_v, i_w in the oscillogram. The arc voltage u_L of the breaker rises to roughly twice the rated d.c. voltage. The duration of the arc is mainly determined by the magnetic energy stored in the inductances, but also by the magnitude of the arc voltage and the rectifier voltage. From the trace of the inverse voltage at the diodes it is possible to judge the voltage stress imposed on them by

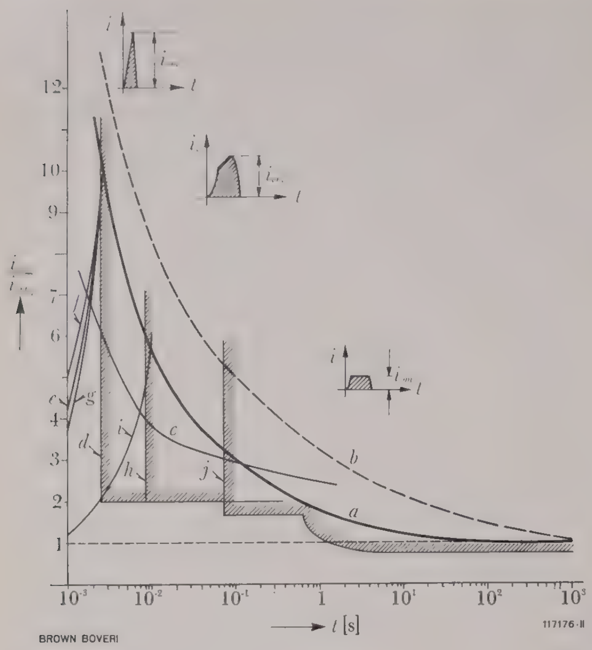

Fig. 15. – Overload characteristics of the DS 200 diode and the regions in which the various protective devices are effective

a = Overload characteristic following rated load
i_{vm} = Peak current
i_{vm1} = Peak value of rated diode current
t = Duration of overload

b = Overload characteristic following no-load

c = Melting characteristic of a partly matched fuse

d = Shorting switch with overcurrent and di/dt trip (i.e. tripping effected the moment a short circuit occurs)

e = Rate of rise of current in the event of an external short circuit; relative inductive voltage drop of 5% at the type current rating of the rectifier, or with smaller d.c. voltage drop and corresponding inductance on the d.c. side. The tripping impulse is given the moment the short circuit occurs.

f = Rate of rise of current in the event of an external short circuit; relative inductive voltage drop of 6%, the tripping impulse was given as a result of overcurrent; otherwise as for e.

g = Rate of rise of current in the event of an internal short circuit; relative inductive voltage drop of 4% at the type current rating of the rectifier.

h = D.C. circuit-breaker with overcurrent and di/dt trip; tripping is effected the moment the short circuit occurs.

i = Rate of rise of current with a limiting choke in the d.c. circuit, or corresponding line inductance.

j = A.C. circuit-breaker with inverse-time overcurrent relay.

interruption. This is greatly diminished by the inductance on the d.c. side.

Silicon rectifiers are often equipped with transductor chokes, enabling the d.c. voltage to be steadily varied within close limits. The chokes have a non-linear inductance which may assume quite a considerable value at low currents. When the d.c. side is interrupted, high transient voltages can be produced. A similar effect is observed with the interphase transformer of the double-star connection in Fig. 13b, the inductance of which becomes high when one three-phase system just ceases to carry current. To prevent the diodes from being harmed by switching overvoltages either when transductor chokes are used, or with interphase transformers, a resistor is connected as a shunt across the d.c. breaker by means of an auxiliary contactor. On interruption, the current first flows through the d.c. breaker for the most part. At low currents, of the order of magnitude of the magnetizing currents of the transductor chokes and interphase transformers, the breaker arc is quenched, the voltage drop of the residual current in the shunt being so small that the diode is not exposed to any harm, from the voltage aspect. The sequence of interruption is thus, first the d.c. breaker, then the a.c. breaker, and finally the auxiliary contactor.

9. Protection of Rectifiers by A.C. Circuit-Breakers

The rectifier installation is switched on and off by a three-phase circuit-breaker. It is equipped with overcurrent relays with instantaneous release and having a current-time characteristic adapted to the overload behaviour of the diodes. It thus protects the rectifier against load surges and the transformer against short circuits. The break times of normal h.v. three-phase breakers are of the order of 50-100 ms, and are generally too long for interruption of rectifier short circuits, having regard to the protection of the semiconductor elements. When an a.c. breaker opens, it can give rise to transient voltages, as dealt with in chapters 5c and 11.

10. Combinations for Overcurrent Protection of Silicon Rectifiers

In Fig. 15 the overload characteristics of the diodes and the regions in which the various protective devices are effective are plotted side by side. From these the following may be deduced:

Fuses afford the most rapid protection. With a rapidly rising short-circuit current they blow in a fraction of a millisecond and, when suitably dimensioned, can also protect diodes against overloads.

Next in speed are the shorting switches, whose time-lag is between 2 and 3 ms. If they are employed, the rectifier transformer must have a sufficiently high impedance voltage, or there must be sufficient inductance on the anode or d.c. sides to retard the rise of the short-circuit current. Fig. 15 also shows some instances in which either the method of tripping—i.e. overcurrent or di/dt tripping—or the inductive drop in d.c. voltage of the rectifier installation was varied. When protection by shorting switches is selected, attention must be paid to the time taken by the short-circuit current to decay (see also chapter 7). Their range commences at a few ms and extends to very long times.

A d.c. circuit-breaker for a silicon rectifier must be quick-acting. The time-lag of modern designs amounts to about 5–12 ms, in older models up to 35 ms. If the rectifier only has a limited overload capacity, an inductance must frequently be provided in the d.c. circuit to limit the rise in the short-circuit current. The rectifier can, however, be dimensioned to carry the short-circuit current during the break time.

Finally, three-phase breakers are used, equipped with definite-time and inverse-current relays, which trip on overload.

In most cases the rectifier is protected by more than one device, the various combinations being described below.

a. Fuses and three-phase breaker

For low-powered silicon rectifiers, which seldom experience short circuits, it is in most cases sufficient to protect the diodes against external and internal shorts by providing fuses with a suitably adapted characteristic. The breaker is used to switch the rectifier on and off for normal operation and may possibly be tripped by its relays if the overload becomes excessively high.

b. Fuses, shorting switch and a.c. breaker

For high-powered rectifiers which seldom experience short circuits, e.g. for electrolysis plants, the above combination of three devices is often employed. The fuses are exclusively provided for the selective disconnection of a defective diode. In the event of a fault, operation can continue unhampered. The shorting switch protects the rectifier against external shorts. For switching on and off, and for overload protection, the a.c. breaker is used.

c. Fuses, d.c. breaker, a.c. breaker

This combination is chosen for rectifier installations liable to experience short circuits fairly frequently, and where the transformer should not be short-circuited every time a fault occurs. This implies, however, that the rectifier be adequately dimensioned with respect to load surges. The fuses can then either be used exclusively to interrupt a defective diode, or as protection against the rarer terminal shorts. The d.c. breaker interrupts line shorts and overloads. The a.c. breaker is merely used to switch the installation on and off.

d. Shorting switch, d.c. breaker, a.c. breaker

If it is not possible or desirable to use fuses, a shorting switch is employed against internal and external terminal shorts, while the d.c. breaker interrupts more remote line faults and overloads. This combination may be used for mains supply rectifiers, the feeders from which are protected with circuit-breakers.

11. Overvoltage Protection

Silicon rectifiers are customarily provided with an ample voltage reserve (see chapter 1), precautions being taken at the same time to avoid or limit overvoltages. The necessary measures were described in

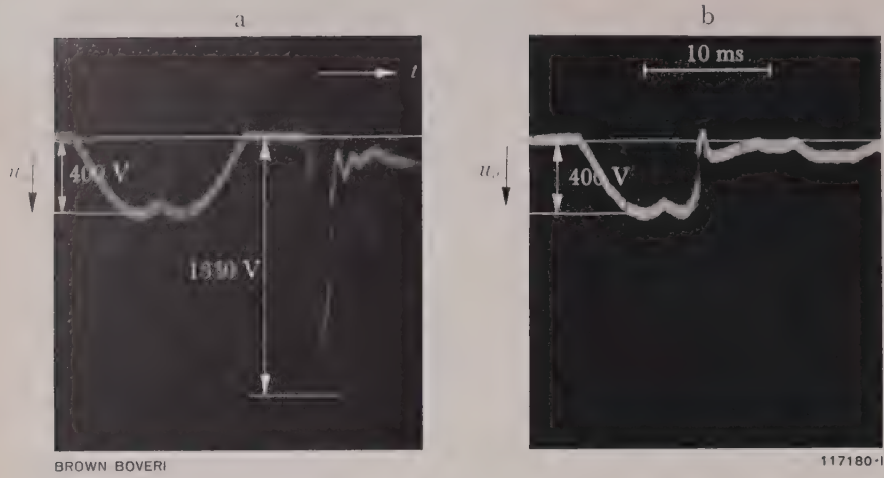

Fig. 16. – Oscillograms of the inverse voltage at the diodes when an unloaded rectifier is switched off

a: Without overvoltage protection

b: With base-load resistors as overvoltage protection

the foregoing chapters. In order to avoid overvoltages when an unloaded rectifier is disconnected, it is usual to connect resistors parallel to the transformer windings just before the breaker is opened, and sometimes for a few seconds on closure. The magnetic energy is then quickly dissipated in the resistors and does not produce any overvoltages. The oscillograms in Fig. 16 show the trace of the inverse voltage of the diodes when an unloaded rectifier is disconnected. If no further steps are taken, inadmissibly high overvoltages may be produced, as seen in Fig. 16a. But if resistors are used as protection against overvoltages on breaking, it is possible to completely avoid overvoltage peaks at the diodes, as shown in Fig. 16b.

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PLANNING SILICON RECTIFIER INSTALLATIONS

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This article discusses the problems arising when silicon rectifier installations are being planned. Special attention is paid to the method of connection chosen, the layout of the equipment, the protective gear and the various control problems. The behaviour on overload and the cooling problems are outlined. To assist in the assessment of the economic performance of installations, curves are given from which the individual losses and the displacement factor can be determined.

THE INCREASING expansion of the industries employing direct current, and the ever-growing powers involved, have resulted in more importance being attached to a.c./d.c. conversion. It is not the object of this article to discuss the monocrystal semiconductor rectifiers, whose development has been furthered by this process, but to provide an overall summary of the installations in which these rectifiers are used. If this goal should prove to be only partly attainable, it must be remembered that semiconductors have only been employed in large-scale installations for a short time and their development is still far from complete. For a review of this kind, if it is not to suffer from lack of clarity, particularly as it deals with a very special subject, it is simplest and also convenient to draw a comparison between the new techniques and those used hitherto. New methods in engineering are only justified if they offer true advantages over known methods. These advantages may be of a technical or economical nature, or reflected in the price.

Comparing the four different methods of conversion: germanium rectifier, silicon rectifier, mechanical rectifier and mercury-arc rectifier, the most striking factor is the high efficiency and insensitivity to temperature of the silicon diodes. Their immediate readiness for operation characterizes the ease with which they can be employed and implicitly expresses the ease with which they can be adapted to the requirements of automatic, unattended installations. These properties are peculiar to all semiconductors, also the ease with which small, handy spare parts can be stored, and the freedom from maintenance. The sole advantage of the germanium rectifier over silicon is its lower voltage drop in the forward direction. However, this advantage can only be utilized at d.c. voltages below about 100 V, and since the general rise in the outputs of rectifiers resulted in the voltages also being increased, few rectifiers are now built with conditions favourable to germanium. The maximum attainable efficiency of the diodes alone is dependent on the ratio of the forward voltage drop to the rated inverse voltage, and this is better for silicon than for germanium, a point which will be raised again in the course of the article.

A factor which severely hampers the use of germanium diodes is the relatively low temperature limit of the crystal, necessitating the provision of expensive equipment to dissipate the heat generated at high ambient temperatures. For the above reasons and the fact that the amount of power converted per unit volume is considerably larger with silicon rectifiers than with germanium, Brown Boveri decided to concentrate solely on the manufacture of silicon diodes. Two different types of diode appear to have gained a certain amount of popularity on the American and European markets, the only difference between them being the height of the respective inverse voltages. Here the following should be borne in mind: In the American terminology it is customary to refer to the PIV or peak inverse voltage, whereas the Euro-

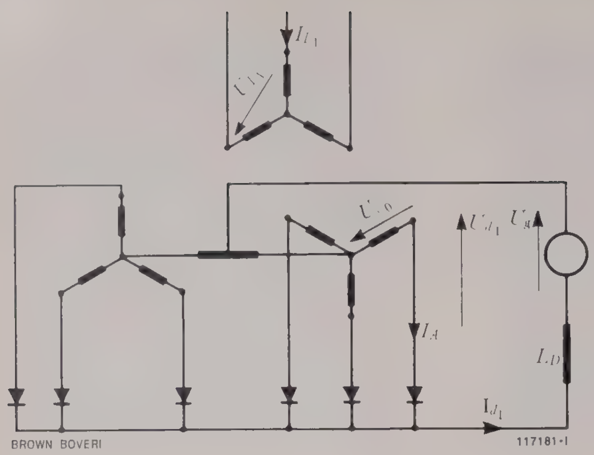


Fig. 1. – Three-phase circuit with interphase transformer

U_{L1} = Primary line voltage
I_{L1} = Primary current
U_{v0} = Secondary voltage of rectifier transformer
I_A = Secondary current (r.m.s. value)
U_{d1} = Rated d.c. voltage
I_{d1} = Rated direct current
U_g = Reverse voltage
L_D = Inductance on the d.c. side

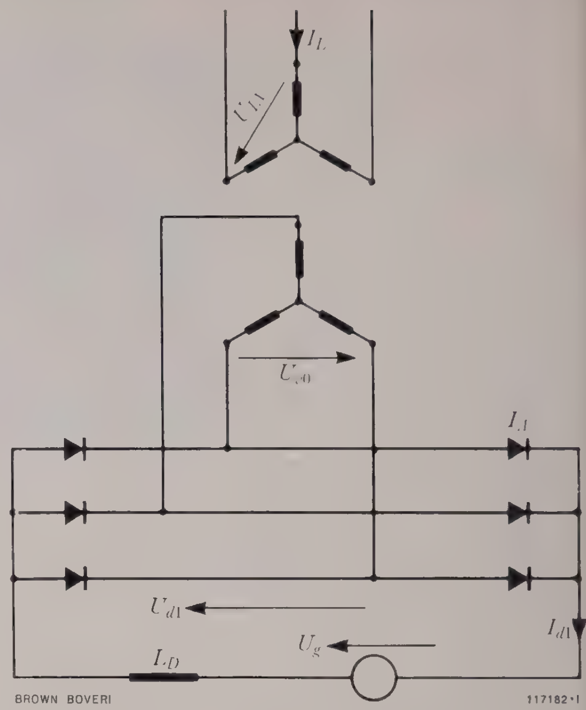


Fig. 2. – Three-phase bridge connection

Notation as for Fig. 1.

pean manufacturers of silicon and germanium diodes give the rated inverse voltage to express the electric strength of the diode. The PIV is roughly equivalent to the maximum test voltage of Brown Boveri diodes. American silicon diodes generally possess operationally utilized inverse voltages of 200 to 300 V. Diodes of the other class have normal inverse voltages of 500–600 V.

Circuitry of Semiconductor Rectifier Installations

All the well-known rectifier circuits can be realized with semiconductor diodes. Owing to their excellent utilization of the valves, those circuits with three-phase commutation stand out among the possible arrangements. Thus for the conversion of three-phase a.c. to d.c. the double-star circuit with interphase transformer and three-phase bridge circuit are almost predominant. In special, heavy-current installations with a relatively low voltage, the customary arrangement has become the triple-two-phase circuit with three-phase interphase transformer. For the conversion of single-phase a.c. into d.c. the single-phase bridge circuit offers certain advantages, and is therefore used almost exclusively in single-phase installations. The basic arrangement of these circuits is

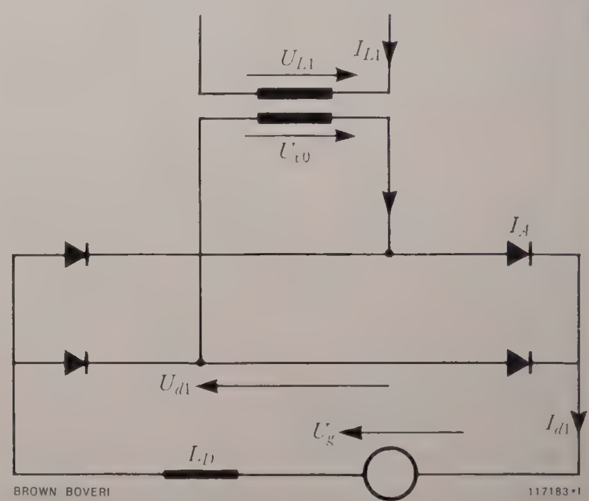


Fig. 3. – Single-phase bridge connection

Notation as for Fig. 1.

illustrated in Fig. 1, 2 and 3. The currents and voltages are labelled with the symbols suggested by IEC, which are used throughout the present article.

The characteristic data of the interphase transformer circuit, the three-phase and the single-phase bridge circuits are listed in the table on page 207. The outstanding difference between the interphase transformer circuit and the three-phase bridge is in the relationship between the design rating P_t of the power transformer and the gross d.c. output given by $U_{di0}\, I_{d1}$. The transformer for the three-phase bridge is designed for a rating 21% less than that for the interphase transformer circuit. Taking into account the additional saving resulting from the ability to dispense with the interphase transformer, the total saving in the outlay for the transformer amounts to about 24–26%. Moreover, the transformer in the three-phase bridge has lower specific copper losses, as will be demonstrated later (see Fig. 14).

Transformer Design

The schematic arrangement and the constructional design of the transformers is amply dealt with in the article beginning on page 215 of this issue. From the comparison between the interphase transformer circuit and the three-phase bridge the greater simplicity of the latter is quite obvious. For twelve or multi-phase installations, within a certain output range, and utilizing a bridge transformer, it is possible to make do with single-deck transformer.

Layout of Semiconductor Rectifier Installations

For the three main fields of application, namely heavy-current installations for electrolysis, substations feeding the overhead wire of railway traction systems, or in locomotives running on an a.c. supply, certain arrangements have already become standard practice. They differ from one another in some of their salient features and will therefore be discussed separately.

Heavy-Current Installations

This category includes installations producing d.c. outputs of 10 kA or more at voltages between 100 and 1000 V. They are typified as a rule by their steady operation and the absence of severe overloads. They are arranged with an eye to maximum possible reliability. This boils down to the fact that when one of several rectifier units operating in parallel develops a fault, the other units remaining in service can continue to produce the full rated current for any length of time or, on the other hand, an operational reserve capacity is provided for the diodes, in that, should one diode fail per transformer phase, those remaining in operation can continue to deliver the full current. In installations which are continuously in service economic considerations bring home the importance of saving every possible kilowatt from the losses.

Fig. 4 shows the schematic diagram of a 40-kA rectifier feeding a chlorine electrolysis plant with three such units to produce a total of 120 kA. A single transformer tank houses the regulating auto-transformer 1 and the rectifier transformer 2 in a double-deck arrangement with intermediate yoke. Also in the same tank are the interphase transformers 10 and the transductor chokes 11. One three-phase winding of one deck feeds one rectifier cabinet, which also contains the shorting switches 3 and reverse-current transformers 4. In the d.c. line of each three-phase system are the overload transformers 6, the choke 7 and the d.c. circuit-breaker 9. The shorting switch 3 is actuated by the current transformers 4 and 6 in the event of a fault in the rectifier elements 5, or if a short circuit occurs on the d.c. side. Having short-circuited the transformer secondary winding, the shorting switch trips the primary circuit-breaker. The installation is planned for minimum losses and therefore contains no fuses. If the interphase transformer circuit were used, a reverse current would flow from the electrolysis bath via the defective diode, or from a parallel rectifier connected to the same busbars. This would be interrupted by the d.c. breaker 9. The choke 7 consists of a primary line with a stack of laminations mounted above it.

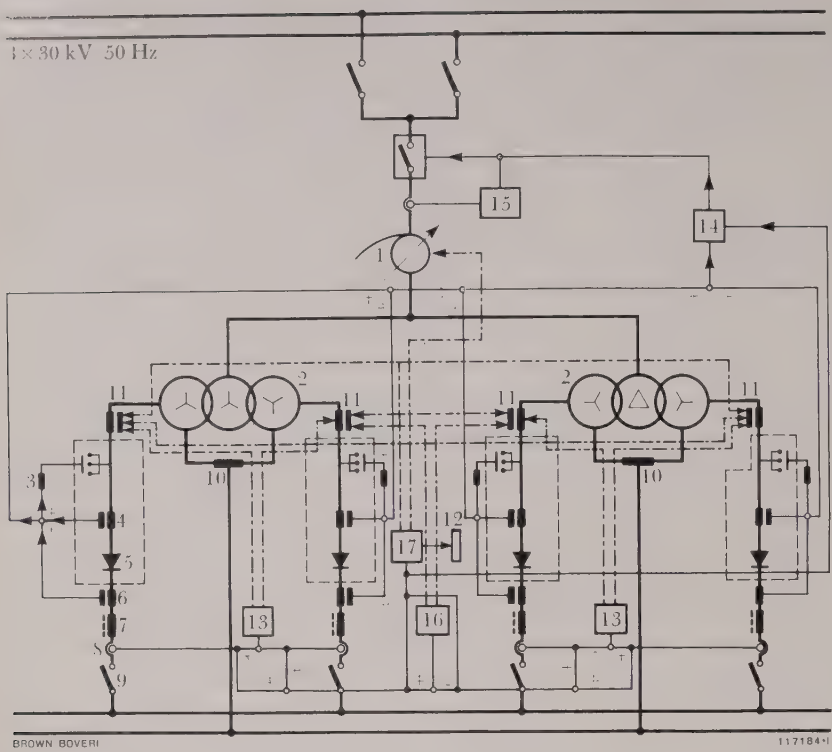


Fig. 4. – Schematic diagram of one group in a heavy-current rectifier installation feeding an electrolysis plant at 3×40 kA, 220 V

1 = Tap-changing auto-transformer
2 = Rectifier transformer
3 = Rectifier cabinets
4 = Reverse-current transformers
5 = Silicon diodes
6 = D.C. overcurrent transformer
7 = Reverse-current chokes
8 = D.C. transformers
9 = D.C. circuit-breakers
10 = Interphase transformer
11 = Transductor choke
12 = To set desired current
13 = Current balancer
14 = Overcurrent relay
15 = Short-circuit protective relay
16 = Current balancer
17 = Current regulator

It only comes into action when a reverse current occurs, because the iron used in it has an almost rectangular hysteresis loop and is brought to saturation by the forward current. The inductance of this choke only increases when a reverse current is produced. The voltage-time area of the choke is such that it only comes into action during the break time of the d.c. breaker 9. The current transformers 8 measure the d.c. of each three-phase system and convey the difference to the regulator 13, which effects a balance in the currents. The difference between the currents of the decks acts on the regulator 16, which effects the balance between the decks. The direct current of all four three-phase systems, i.e. the rectifier unit per transformer, is kept constant by regulator 17, which at the same time attends to the operation of the tap changer of transformer 1.

In installations where, in the event of a diode failing, it is inadmissible for the current to be temporarily reduced during the time needed to replace the diode, as is the case with electrolysis of molten-flux baths kept just above the freezing point, protection is afforded by fuses. The fuses selectively disconnect the affected point in the rectifier cabinet, which remains in operation without any reduction in the current. Of course higher losses must be accepted in this case, as will be shown later. The d.c. breaker 9 may then be dispensed with.

Substations Feeding the Overhead Wire of Railway Traction Systems

A feature of such installations is that they must be capable of withstanding periodically recurring overloads. Often the silicon rectifier has to be connected in parallel with a mercury-arc rectifier installation, either direct via the busbars or through the overhead line. The selective disconnection of the feeders by the feeder breakers in the event of a fault, imposes special conditions regarding the layout of the silicon rectifier. In Fig. 5 an example is chosen, showing an installation operating in parallel with a mercury-arc rectifier to feed four branch lines. The voltage is supposed to be 750 V d.c., which is obtained by a three-phase bridge circuit with two series diodes in each limb of

the bridge. The rectifier transformer 1 feeds the rectifier cabinet 3, protected against overvoltages from the a.c. mains or from the overhead line by the overvoltage protection devices 2 and 4. The d.c. circuit contains the d.c. breaker 6 and the choke 5.

The feeder breakers are equipped with a release which trips at a set overcurrent, and another which responds to the rate of rise of current. The impedances 9 are represented by the line resistance and the inductances of the feeders. If the mercury-arc rectifier causes a short circuit on the busbars due to a backfire, the silicon rectifier supplies a short-circuit current into the busbars. The d.c. breaker 10 of the mercury-arc rectifier responds to the reverse current and disconnects the affected rectifier from the busbars. The choke 5 of the silicon rectifier is so designed that, during the time-lag before the breaker 10 opens, the short-circuit current supplied by the silicon rectifier is prevented from rising to such a height that disconnection of the silicon rectifier becomes necessary. In the event of a short circuit on the contact wire, the short-circuit current flows through the particular feeder breaker 8 concerned and is damped by the impedances 5 and 9. These impedances must be so designed that the current is prevented from rising to a harmful level in the silicon rectifier during the break time of the feeder breaker. Usually this condition is easier to fulfil, the more branch lines there are connected to the busbars of the substation. The larger the number of feeders, the smaller the feeder currents and the lower the pick-up currents of the feeder breakers become, while the line impedances of the feeders increase.

If other rectifier substations are connected in parallel via the overhead contact wire, the above condition is also simplified because the other stations then also help to produce the short-circuit current, so that a heavier current flows through breaker 8 than through 6. The same applies to the rate of change in the current, for which reason the feeder breakers are equipped with a dI/dt release. In contrast, the overloads normally occurring in service must be withstood by the silicon units, as will be explained later.

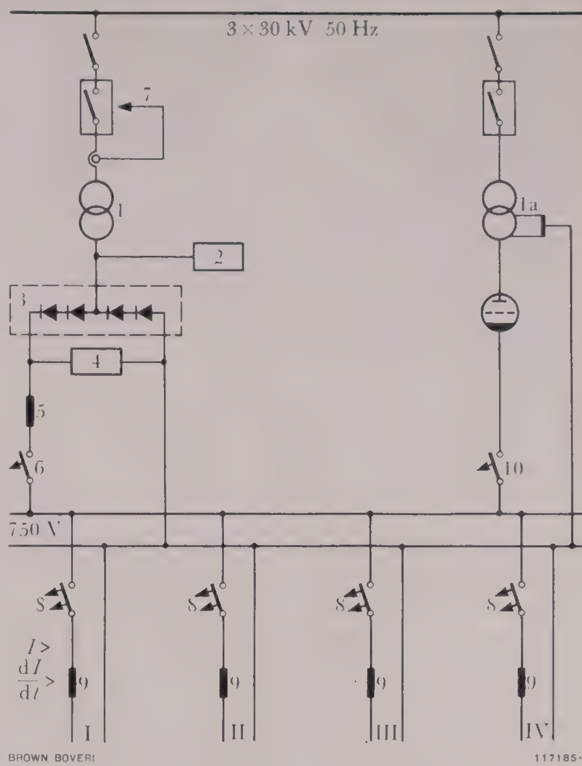


Fig. 5. – Schematic diagram of a silicon rectifier operating in parallel with a mercury-arc rectifier, feeding the contact wire for railway traction

1 = Rectifier transformer
1 a = Transformer of parallel rectifier
2 = Overvoltage protection
3 = Rectifier cabinet, three-phase bridge connection, pairs of diodes in series
4 = Overvoltage protection
5 = D.C. choke
6 = D.C. circuit-breaker
7 = Primary circuit-breaker
8 = Feeder breakers
9 = Line inductances
10 = D.C. breaker of mercury-arc rectifier
I, II, III, IV = Feeders

Rectifiers in Locomotives

It is now some years since mercury-arc rectifiers were first used in locomotives to convert the power supplied over the a.c. line into the direct current required by the traction motors. For example, in Italy there are 14 dual-system motor-coaches with Brown Boveri mutators, which can run off either 3000 V d.c. or 3300 V, $16^2/_3$ c/s, three-phase a.c., with a one-hour rating of 760 kW per motor-coach. For heavy duties in connection with the removal of

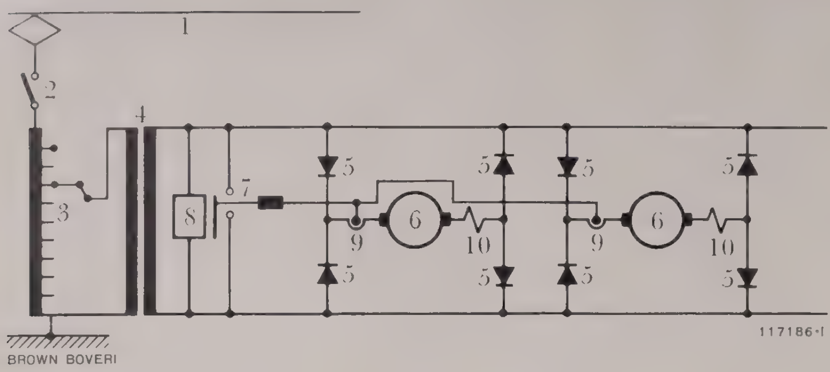


Fig. 6. – Schematic diagram of a silicon rectifier used in a traction vehicle

1 = Contact wire, e.g. 25 kV, 50 c/s
2 = Primary breaker
3 = Tap-changing transformer
4 = Rectifier transformer
5 = Silicon rectifier (limb of bridge)
6 = Traction motors
7 = Shorting switch
8 = Overvoltage protection
9 = Overcurrent transformer
10 = Smoothing chokes

overburden from open-cast mines in Germany, eleven locomotives have been supplied to run off a 50-c/s supply at 6 kV, developing about 2000 kW per unit. The mercury-arc rectifiers have given excellent service under these heavy-duty conditions.

However, the silicon rectifier is also ideal for this form of operation. Owing to its insensitivity to abrupt mechanical load surges and the flexibility of the general layout it has also been successfully introduced into this field in recent years. The basic arrangement of an installation of this kind is illustrated in Fig. 6. The supply from the contact wire 1 is either at 25 kV, 50 c/s or 15 kV, $16^2/_3$ c/s to the transformer 3. This is designed as a tap-changing auto-transformer and is connected to the rectifier transformer 4 which feeds the two single-phase bridge circuits each comprising four limbs 5 equipped with silicon diodes. The traction motors 6 are connected to the d.c. terminals. The current transformers 9 feed the shorting switch 7 which, on the occurrence of a fault, causes the rectifiers to be disconnected from the transformers, followed by the interruption of the supply from the contact wire by means of the main breaker 2. The overvoltage protection device 8 prevents harmful overvoltages from affecting the diodes. As regards the overload behaviour of this installation the remarks made under the foregoing heading also apply in this case. In practice the rectifier is dimensioned on the basis of the starting current of the traction motors and the maximum inverse voltage, and taking into account fluctuation of the mains voltage.[1]

[1] See also E. KOCHER: 50-c/s and Multi-system Traction. Brown Boveri Rev. 1960, Vol. 47, No. 9, p. 582–97, with special reference to pp. 584–8.

Repercussions on the Supply Network and cos φ

The rules applying to silicon rectifiers in this respect are the same as those which have become standard practice for all other types of rectifier. Here the smaller impedance voltage of the transformer compared with that in mercury-arc rectifier installations exerts a beneficial influence. Furthermore, the bridge circuits make it easier to produce arrangements with a pulse number of twelve or more.[2]

Fig. 7 reproduces the schematic arrangement of a silicon rectifier installation. The transformer should possess a relative impedance voltage e_K, and the transductor chokes and any busbar inductances should have a reactance of x_b. To calculate the displacement factor it is necessary to know the relative inductive d.c. voltage drop d_{x1}. This comprises the inductive d.c. voltage drop due to the transformer d_{xt1}, the inductive d.c. voltage drop due to the a.c. system reactance d_{xL1}, and the inductive d.c. voltage drop due to the inductances present on the secondary side d_{xb1}. Fig. 8 and 9 show the connection between the displacement factor $\cos\varphi_1'$ and the total inductive d.c. voltage drop d_{x1} for hexapulse and twelve-pulse installations. The displacement factor $\cos\varphi_1'$ is the total power factor of the fundamental wave on the secondary side with a delay angle of $\alpha = 0$, without allowance for the no-load current of the transformer. Fig. 10 plots the actual displacement factor $\cos\varphi$ at the primary terminals for different delay angles α. The parameter of these curves is the no-load (or magnetizing) current

[2] See pages 215–27 of this issue.

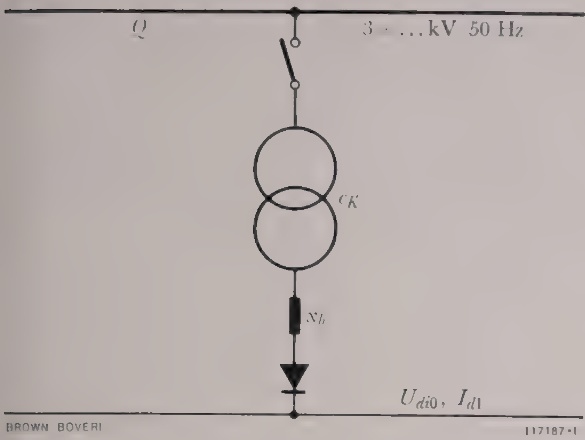


Fig. 7. – Schematic diagram of a semiconductor rectifier installation

e_K = Impedance voltage of the rectifier transformer

Q = Short-circuit power of the primary network

x_b = Reactance of busbars, etc. on the secondary side of the transformer

U_{dio} = Ideal no-load d.c. voltage

I_{d1} = Rated direct current

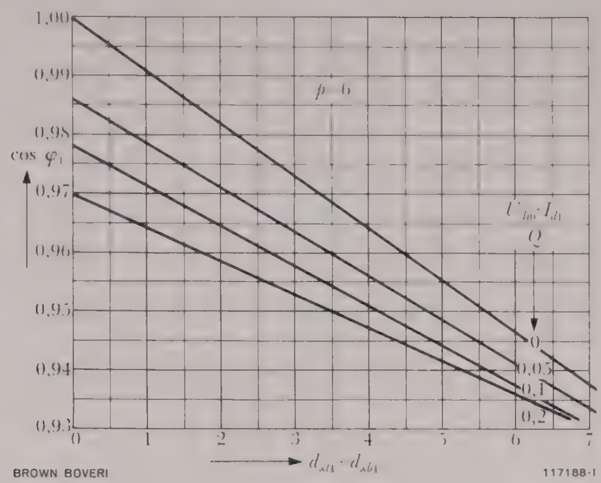


Fig. 8. – Displacement factor with $\alpha = 0, p = 6$

$\cos\varphi'_1$ = Displacement factor at $\alpha = 0$, without regard to the magnetizing current of the transformer

$\frac{U_{di0} \cdot I_{d1}}{Q}$ = Gross d.c. output referred to the short-circuit power of the network

$d_{xt1} + d_{xb1}$ = Inductive d.c. voltage drop at the transformer and in the secondary reactances ($d_{xt1} = 0{\cdot}5\ e_K$ for three-phase bridge and interphase transformer connections)

of the transformer expressed as a percentage of the line-side current at rated load.[3] It will be recognized from Fig. 8 and 9 that the displacement factor decreases rapidly with increasing inductive d.c. voltage drop at zero delay angle. In order to avoid unnecessary reactive powers it is therefore logical to make the impedance voltage of the transformer as low as possible. From the above-mentioned diagrams it is also possible to estimate the effect of the mains impedance which, as will be seen, grows with a hexapulse system, i.e. reducing the short-circuit power of the network and causing the displacement factor to deteriorate still further, whereas in twelve-pulse installations, in a definite range, precisely the opposite occurs. The additional effect of the no-load current of the transformer on the displacement factor with and without phase control by delay angle may be seen in Fig. 10.

When studying the repercussions of the rectifier installation on the a.c. system it must be remembered that the current harmonics caused by the rectifier are superposed on the primary side. This is based on the conventional assumption that the direct current is fully smoothed, which is adequately true for the majority of installations. Harmonics whose ordinal number is divisible by three do not occur on the primary side of symmetrical rectifier installations. Hence only the 5th, 7th, 11th, 13th and higher harmonics need to be considered. The n-th harmonic,

[3] Taken from IEC publication No. 84, 1957.

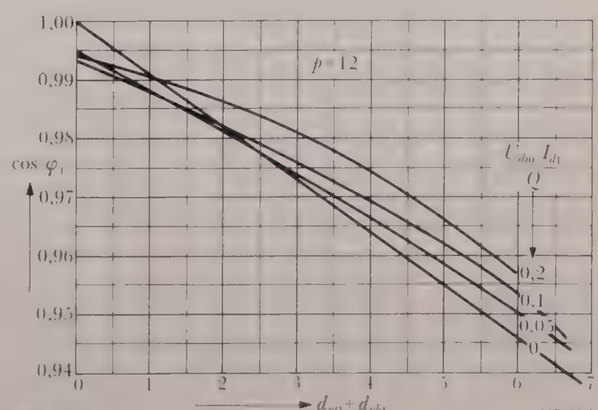


Fig. 9. – Displacement factor with $\alpha = 0, p = 12$

Notation as for Fig. 8.

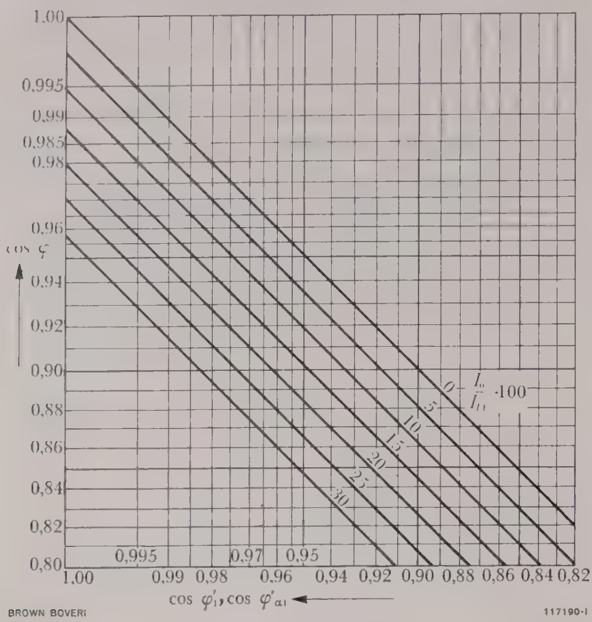


Fig. 10. – Displacement factor at different values of α with $p = 6$ and $p = 12$, taking the magnetizing current into account

$\cos\varphi_1$ = Rated displacement factor
$\cos\varphi'_1$ = Displacement factor from Fig. 8 or 9
$\cos\varphi'_{\alpha 1}$ = Displacement factor at delay angle α. Magnetizing current $I_0 = 0, 5, 10, 15, 20, 25, 30\,\%$ of rated primary current of the rectifier transformer I_{L1}

disregarding overlap and with a delay angle $\cos\alpha = 1$, is related to the d.c. power and the primary voltage by the following formula

$$I_{ni_1} = \frac{1}{n} \cdot \frac{U_{di_0} \cdot I_{d_1}}{\sqrt{3}\, U_{L_1}}$$

in which n = the ordinal number of the harmonic
U_{di_0} = the ideal no-load d.c. voltage
I_{d_1} = the rated direct current
U_{L_1} = the rated voltage of the line winding of the transformer
I_{ni_1} = the ideal r.m.s. value of the a.c. line current harmonic of the n-th order, for $\alpha = 0$ and $d_{x1} = 0$

The effect of the transformer impedance voltage and the delay angle is of minor importance. This relationship is well illustrated in IEC publication No. 84, 1957.

In installations fed via step-down transformers from the national grid, where the busbars may possibly have generators connected in parallel, it is important to ensure that the current harmonics are mainly supplied by the generators feeding the medium-voltage network. The damping windings of such generators must therefore be specially dimensioned to withstand the harmonics occurring. In such cases it is preferable to adopt a pulse number of twelve or higher.

Control of Semiconductor Rectifier Installations

Since the semiconductor diodes, unlike mechanical or mercury-arc rectifiers, cannot be controlled, special methods have to be adopted to vary the d.c. voltage between the tappings of the tap-changing transformer. In general, the a.c. voltages applied to the elements are varied in steps by tap-changing transformers, of which there are two distinct groups:

1. One in which the secondary voltage is varied by altering the number of turns of the primary winding. This is quite a cheap method of varying the d.c. voltage in the ratio 1:3 to 1:4, assuming that the primary voltage is relatively low (10–30 kV).
2. The other method, for higher primary voltages (60–110 kV) is to employ step-down transformers, preferably in the form of auto-transformers.

Since the variation of the a.c. voltage is effected by means of a tap changer, there must be some additional means of providing the fine control between the tappings. For this task transductor chokes are often employed. Fig. 11 shows the layout of a control system for an electrolysis plant. The regulator 5 attends to the distribution of the load between the two secondary windings of the rectifier transformer 1. At the input to this regulator the difference between these two partial currents is applied, the premagnetization currents of the transductor chokes 2 appearing at the output. The total direct current is applied to the regulator 6 as actual value, being compared therein with the desired value set by potentiometer 8 to control the two transductor chokes 2 jointly. When the control range of the chokes is

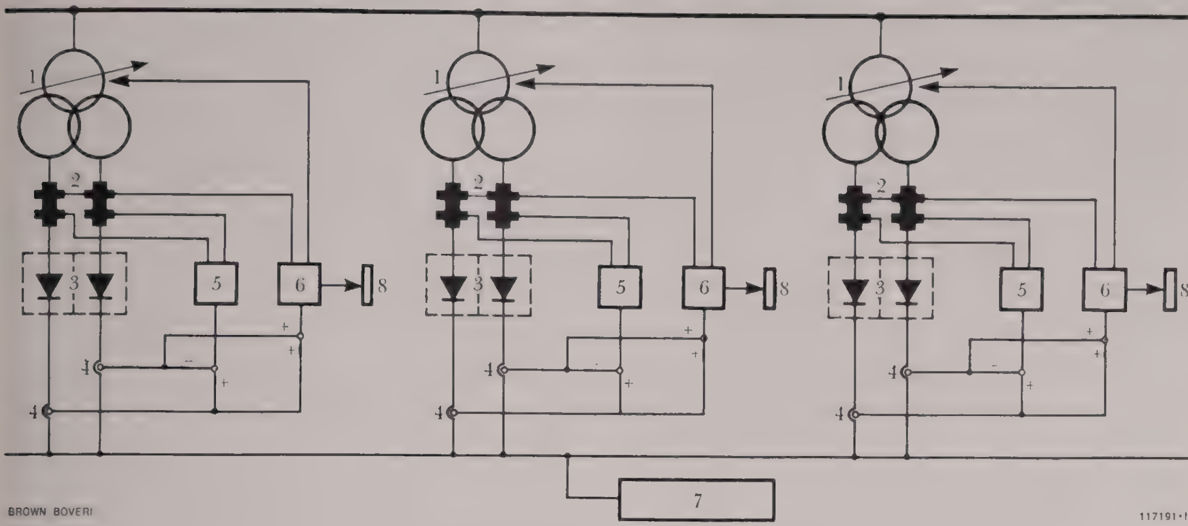


Fig. 11. – Schematic diagram showing the control of an electrolysis rectifier

1 = Rectifier transformer with tap changer
2 = Transductor chokes
3 = Rectifier cabinets
4 = D.C. transformer
5 = Current balancer
6 = Current regulator
7 = Electrolysis bath
8 = To set the desired current value

exhausted, the tap changer of the rectifier transformer is advanced by regulator 6.

Fig. 12 illustrates the combined operation of the d.c. control system with an electrolysis bath, and its consequences from the design aspect and for the protection of the installation, having regard to the rules laid down on page 195. Line 1 in the voltage-current diagram represents the characteristic of the electrolysis bath. Line 2 represents the overall voltage-current curve of all three rectifiers in Fig. 11. The characteristics 1 and 2 intersect at the U_1, I_2, the working point of the installation. If now, for instance, one of the three rectifiers fails due to a fault, the characteristic 2 changes in such a manner that it assumes the position 3. This curve now intersects the characteristic of the bath at the current I_3, and this will be obtained to begin with. But this current represents an overload for the two rectifier units still in operation, if they are only dimensioned for a current of $^2/_3\ I_2$. Therefore the characteristic 3 must experience a parallel displacement, either by varying the secondary a.c. voltage, or by reducing the voltage with the aid of the transductor chokes 2, until the curve is in the position 5. The current I_5 would then correspond to $^2/_3\ I_2$. The installation must be designed so that the range of control of the transductor chokes is sufficiently wide to relieve the overloaded rectifier units within a time compatible to the silicon rectifier. Otherwise the tap changer must be able to effect the necessary changes within a suitable period. The steeper the characteristic of the bath and the

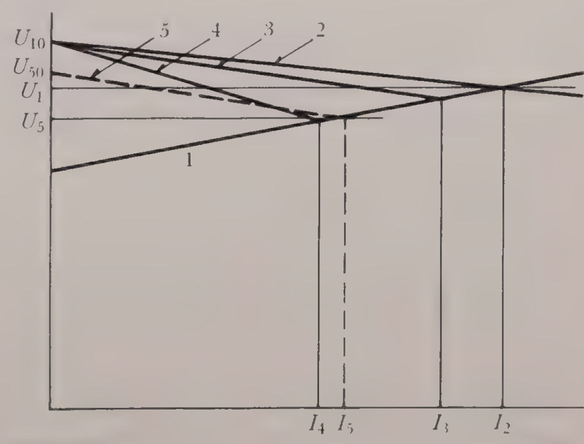


Fig. 12. – Load diagram of an electrolysis rectifier (current-voltage characteristic)

1 = Characteristic of the electrolysis bath
2 = Load characteristic of three units
3 = Load characteristic of two units
4 = Load characteristic of one unit
(2–4) at no-load d.c. voltage U_{10}
5 = Load characteristic of two units at the no-load voltage U_{50}

slower the tap changer operates, the worse conditions become.

Another method of control is to use three single-phase tap changers, as is done on electric traction vehicles,[4] instead of a single three-phase tap changer. These 32-step changers, designed for a maximum upward speed of 0·3 s per tap, are ideal for use with rectifier installations feeding aluminium electrolysis plants. When the three tap changers are asymmetrically controlled, a total of 96 taps is obtained. It is thus possible to dispense with transductor choke control between two transformer taps in most cases. The displacement factor will then vary between about 0·9 and 0·95, even when the system is used to correct anode effects. The excellent resistance of the tap changer to wear exerts a beneficial effect on the expenditure for maintenance. Brown Boveri are supplying a silicon rectifier based on this control principle, having a rating of 90 kA at 475 V for the electrolysis of aluminium, with facilities for expansion to 90 kA at 900 V.

[4] W. BILLETER: High-Voltage Tap Changers for A.C. Locomotives. Brown Boveri Rev. 1960, Vol. 47, No. 9, p. 549–55.

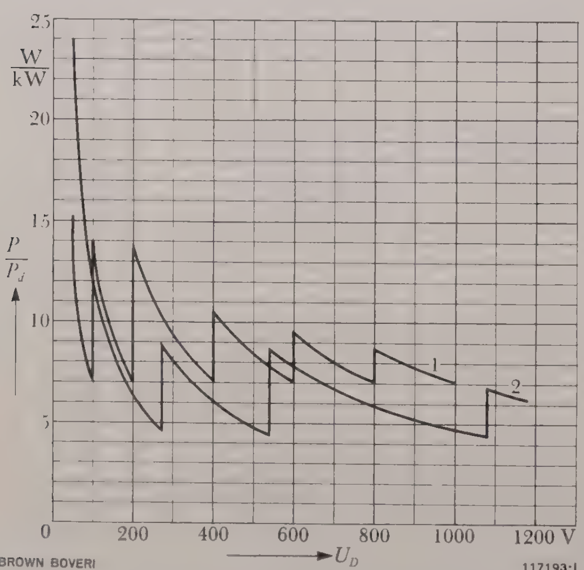


Fig. 13. – Relative losses of germanium and silicon diodes

U_D = D.C. voltage
P_v = Diode losses in W
P_d = D.C. output in kW

Curve 1: For germanium rectifier
2: For silicon rectifier

Losses

Special attention has to be paid to the efficiency of semiconductor rectifiers which are continuously in operation, converting large powers. Every kilowatt by which the losses can be reduced represents a considerable gain. For the user the design of the installation with respect to the losses or the efficiency is of major importance, particularly as regards the capital investment, the interest yield and the cost of current. In large installations, where efficiencies of 0·96–0·98 or more are attained, it is more convenient to consider the losses of the individual rectifier units when comparing the economics of different systems. This method is adopted in the remarks which follow, the losses being divided into three separate headings.

Diode Losses

Fig. 13 shows the diode losses for germanium and silicon rectifiers as a function of the d.c. voltage. It will be seen that for voltages over 100 V the losses of the germanium diode are less than those of silicon. For higher voltages the silicon rectifier is more economical. The points of discontinuity on the two curves are due to the change in the circuit arrangement, i.e. from interphase transformer to three-phase bridge, or by the series connection of a number of elements. From the curves it may be recognized that, with increasing d.c. voltage, the diode losses in W per kW of converted power decrease, and with silicon rectifiers tend towards a limit of about 4·5 W/kW at very high voltages. This figure is given by the voltage drop per diode and the maximum admissible inverse voltage.

Transformer Losses

Whereas the losses of the stack can be easily worked out on the basis of simple considerations this is not the case with the transformer losses. Here it is necessary to distinguish between the two kinds of losses: namely the iron losses and the copper losses in the transformer. The former differ little from those of an ordinary mains transformer, but the copper losses are dependent on a number of factors. On

examining the Fig. 1 and 2 it will be observed that the transformer for the circuit with interphase transformer has more complicated interconnecting leads than the three-phase bridge circuit. Furthermore, the type rating of the former is larger than that of the bridge transformer, for the same d.c. output: hence the transformer losses cannot be expressed simply in terms of the d.c. voltage, like the diode losses. Consequently for the representation of the transformer losses, characteristics were chosen in which the copper and iron losses of the transformers are shown separately for the two rectifier circuits, as a function of the converted d.c. power (Fig. 14). By way of comparison the losses of an ordinary distribution transformer are also shown. The hatched areas have been confirmed by installations actually executed, or planned. They show that the copper losses of the transformers for the bridge circuit and the interphase transformer circuit decrease quite sharply with increasing d.c. output. On this account it is more economical to choose large transformer units. How large the transformer rating shall be for a definite installation and into how many units this shall be divided is governed by the safety requirements, capital investment, the rate of interest and the cost of electricity.

Other Losses

Apart from the diode losses and the transformer losses, the largest losses occur in the fuses and busbars. Fig. 15 shows the fuse losses in W per kW of converted power. The region between the curves 1 and 4 is determined by the different qualities of the fuses. The Brown Boveri fuses which are used at present yield values conforming to curve 1 as a result of the special design of the fuse-wire. Special attention must be paid to this point during planning, as there are a number of fuses which yield values approaching those in curve 4. The effect of the percentage to which the current capacity of the diodes and, in consequence, the fuses is utilized at loads of 70–85 % of rated load, is shown for Brown Boveri fuses by the curves 2 and 3. The discontinuity of these curves is also the result of changing from interphase transformer to bridge connection.

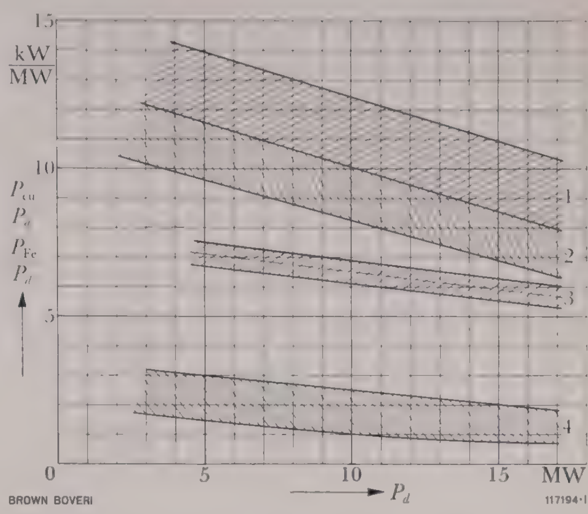


Fig. 14. – Relative transformer losses

Band 1 = Copper losses of a transformer in a circuit with interphase transformer

Band 2 = Copper losses of a three-phase bridge transformer

Band 3 = Copper losses of an ordinary distribution transformer

Band 4 = Iron losses of either type of rectifier transformer

applying to primary voltages of 10–20 kV and an impedance voltage of $e_K \approx 7\%$

P_{Cu} = Copper losses in kW
P_{Fe} = Iron losses in kW
P_d = D.C. output in MW

Fig. 16 shows the losses on the bars connecting the transformer and the rectifier, as well as the losses per metre on the d.c. busbars. For three-phase busbars the single length counts, for d.c. busbars the total length must be allowed. In order to recognize the effect of the current density, all the curves were plotted for the three densities of 1·5, 1 and 0·7 A/mm².

From the curves of the losses as a function of the output or voltage, it will be recognized that the losses in the transformer, diodes, busbars and fuses are all roughly of the same order of magnitude, provided the bars are not longer than about 10 m. There is therefore no point in dealing with any one of the loss sources specially, assuming the others to be given. Above all it is important to decide how large the transformer rating must be, what service voltage is suitable, and in what manner the semiconductor elements should be protected. Good planning can often help to amortize quite high initial outlay in a

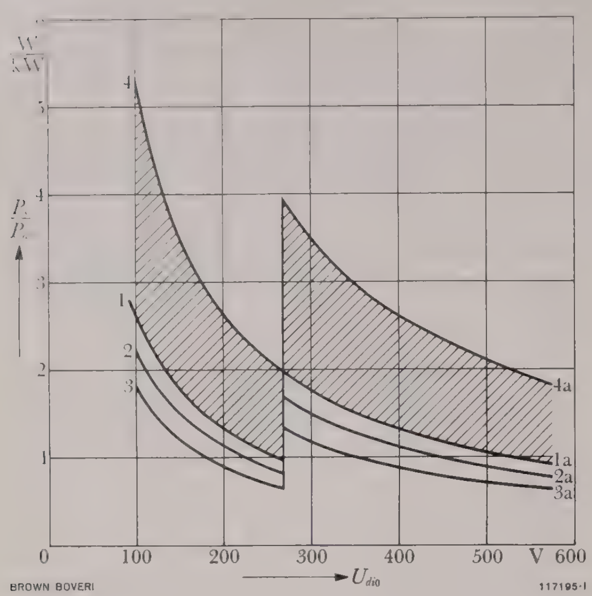


Fig. 15. – Relative fuse losses

Interphase transformer circuit:

Curve 1: Fuse 100% loaded
2: Fuse 85% loaded
3: Fuse 70% loaded
4: Fuse 100% loaded

Brown Boveri fuse type GLB 4

Three-phase bridge circuit:

Curve 1a: Fuse 100% loaded
2a: Fuse 85% loaded
3a: Fuse 70% loaded
4a: Fuse 100% loaded

Brown Boveri fuse type GLB 4

P_s = Fuse losses in W
P_d = D.C. output in kW
U_{dio} = Ideal no-load d.c. voltage

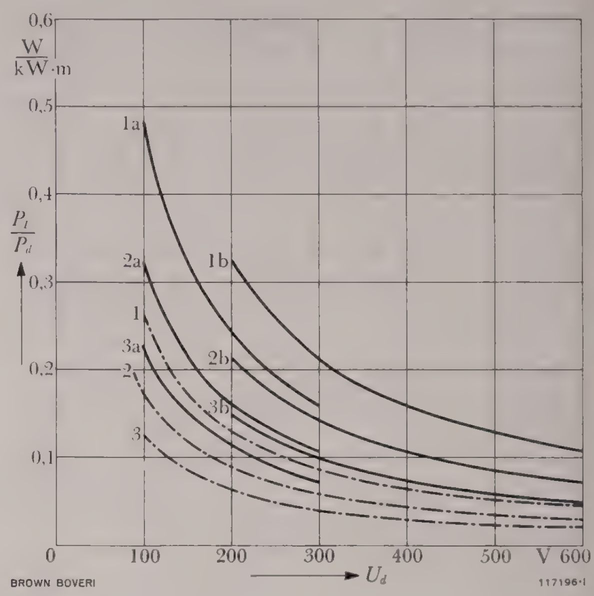


Fig. 16. – Relative busbar losses

Curves 1, 2, 3 = Current densities of 1·5, 1, 0·7 A/mm² on the d.c. busbars

Curves 1a, 2a, 3a = The same current densities on the secondary bars in the circuit with interphase transformer

Curves 1b, 2b, 3b = The same current densities on the secondary bars of the three-phase bridge circuit

For the d.c. busbars the length is given by the total length of the bars in m, whereas for the transformer secondary bars only the single distance between the transformer and the rectifier terminals applies.

P_L = Busbar losses in W
P_d = D.C. output in kW
U_d = D.C. voltage

short space of time, a point which cannot be taken into account early enough, paying due respect to the interest on the capital and the cost of electricity.

Behaviour on Overload

It is a difficult problem to analyse the thermal behaviour of a semiconductor rectifier, since it is a polydimensional problem of thermal conductivity with numerous heat stores and sources.[5] However, with some simplifications, it is possible to produce a valid equivalent diagram. Considering the diagram in Fig. 17 and substituting some numerical values, it will at once be recognized that the first time constant $\frac{1}{2}W_1C_1$ and the time constant $(W_1 + W_2/2)\ C_2$ differs from the time constant $(W_1 + W_2 + W_3/2)\ C_3$ by at least three to five orders of magnitude. The stores C_1, C_2 and C_3 represent the heat storage capacity of the crystal, the soldered joint and the layers in immediate contact with the crystal, as well as the heat capacity of the cooler. For actions which last longer than 1 s the two capacities C_1 and C_2 may be assumed not to be present, the diagram being thereby simplified to that shown in Fig. 18. Thus, the overload capacity of a rectifier circuit is primarily determined by the time constant of the cooler. This is a

[5] O. JAKITS: The Thermal Behaviour of Semiconductor Rectifiers. Brown Boveri Rev. 1958, Vol. 45, No. 11/12, p. 540–4.

material constant with opportunities for slight variation according to the particular design employed. For the copper coolers employed almost exclusively its value varies very little. The resistance to heat transfer between the cooler and coolant can, however, be appreciably reduced by good design. The function f_1 in the diagram (Fig. 18) gives the relationship between the waste heat generated and the current producing it. It has a definite value for a given circuit and a definite forward characteristic of the diodes. If for this simplified thermal diagram the values for the cooler and diode were to be substituted, a family of curves (Fig. 20) would be obtained for an overload as represented by Fig. 19. The dimensioning factor Γ denotes by what multiple an installation must be over-dimensioned compared with a basic load current I_{d_1} as in Fig. 19, in order to withstand the overload peaks occurring, without the temperature of the semiconductor wafer exceeding the normally admissible level.

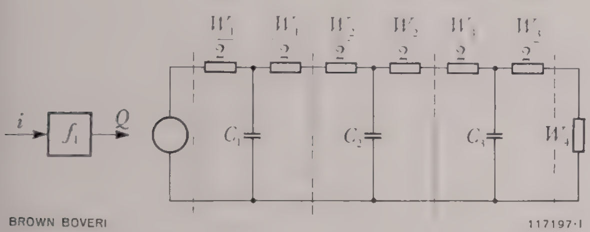


Fig. 17. – Simplified thermal diagram of a semiconductor diode with its cooler

W_1 = Thermal resistance of the crystal in °C/W
W_2 = Thermal resistance of the soldered joints and the layers in immediate contact with the semiconductor wafer
W_3 = Thermal resistance of the cooler
W_4 = Thermal resistance of the boundary layer between cooler surface and coolant, e.g. air at a speed of v m/s
C_1 = Mean heat capacity of the crystal in J/°C
C_2 = Mean heat capacity of the soldered joints and the layers in immediate contact with the semiconductor wafer
C_3 = Mean heat capacity of the cooler
i = Mean value of load current
f_1 = Function expressing the relationship between the load current i and the waste heat Q. f_1 is a function of the form of the forward characteristic and circuitry
Q = Waste heat in W

Order of magnitude of time constants:

$$W_1C_1/2 = \text{approx. } 100\text{–}200\ \mu\text{s}$$
$$(W_1 + W_2/2)C_2 = \text{approx. } 200\ \text{ms}$$
$$(W_1 + W_2 + W_3/2)C_3 = \text{approx. } 100\text{–}200\ \text{s}$$

Cooling System

In semiconductor rectifier installations there are two distinct types of cooling system—parallel and series cooling. The advantage of parallel cooling is that all diodes are cooled with air at ambient temperature. The velocity of the air is low, the cross-sections large, which appreciably reduces the amount of noise produced. The disadvantage of parallel cooling is that careful constructive arrangement of the air circuits is necessary in order to achieve a uniform air distribution. The series cooling system operates with much smaller cross-sections but, in consequence, much higher velocities. With series cooling an important point is to ensure that the last cooler element receives air at a sufficiently low temperature to avoid over-heating, particularly in the event of overload surges, as indicated in the previous chapter. In order to provide an adequate safety margin, the overload behaviour must be related

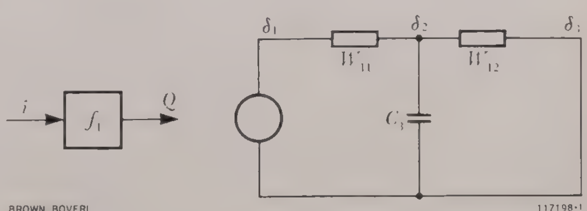


Fig. 18. – Simplified thermal diagram of a semiconductor diode with cooler, for times longer than 1 s

i = Mean value of load current
f_1 = Function expressing the relationship between i and Q
Q = Waste heat in W
C_3 = Mean heat capacity of the cooler in J/°C
W_{11} = Thermal resistance of cooler and diode in °C/W
$W_{11} = W_1 + W_2 + W_3/2$
W_{12} = Thermal resistance between cooler and air
$W_{12} = W_3/2 + W_4$
δ_1 = Temperature of crystal
δ_2 = Temperature of cooler near crystal (in test orifice of diode body) in °C
δ_3 = Temperature of coolant in °C at inlet

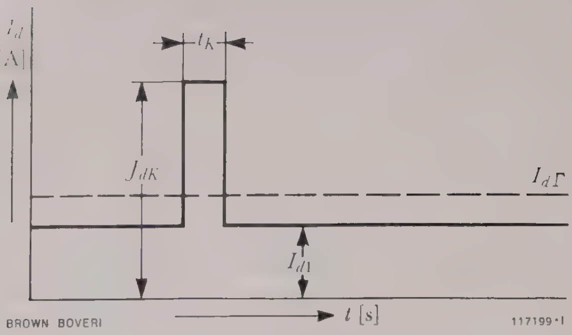


Fig. 19. – Overload diagram

I_{d1} = Rated current, continuous on d.c. side in A
I_{dK} = Overload current in A
$I_{d\Gamma}$ = Design current of the rectifier in A
t_K = Duration of overload in s
$1\ \mathrm{s} \leqslant t_K \leqslant 600\ \mathrm{s}$

to the most unfavourably situated, i.e. the last, diode in the cooling circuit.

The coolers can be designed in two distinct ways. Either each diode may be allocated its own cooler, or a number of parallel diodes, e.g. five or six, may have a combined cooler block (see Fig. 21 a and b). The advantage of the latter system over the former

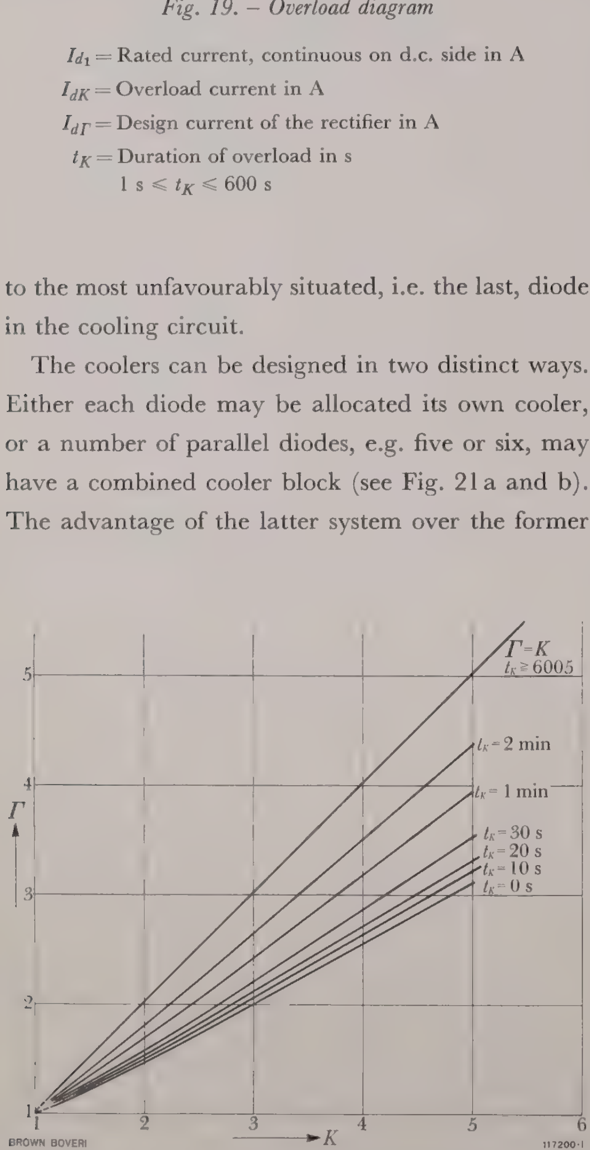


Fig. 20. – Dimensioning curves for overload stresses on silicon rectifiers

$K = I_{dK}/I_{d1}$ = Overload factor
$\Gamma = I_{d\Gamma}/I_{d1}$ = Dimensioning factor
t_K = Duration of overload

is that, owing to the inevitable differences in the current distribution between the parallel diodes, some of the diodes are obliged to carry a heavier current than the mean value. The temperature of the cooler block assumes a value corresponding to the mean value of all the parallel diodes, since the possible temperature gradient in steady-state operation with a solid block can only be very small. On the other hand, as there is no relationship between the thermal resistance of a diode and its normal forward characteristic, and therefore no connection between the current distribution and the thermal resistance, it is possible with this system for a diode, even though it may be carrying the heaviest current of a number of parallel diodes, to have a lower temperature in the semiconductor layer than another diode carrying a lower current. But since the differences between the thermal resistances are very small, provided the diodes are manufactured properly and under uniform conditions, it is possible for the current capacity with a cooler block common to several parallel diodes to be better than with individually cooled diodes; in other words, with the same current capacity the safety margin to the limiting temperature is greater when common coolers are employed. With separate coolers and unequal current distribution the temperature of the cooler is only dependent on the losses generated in the corresponding diode. In this case the temperature of the semiconductor wafer must be expected to be less uniform.

If series cooling is employed with individual coolers, the improbable, yet not entirely impossible case may occur, in which the diode generating the most heat is also the last in the cooling circuit. This would expose the diode to great risk of overheating, a fact which would have to be fully taken into account when planning the installation.

Protection of Semiconductor Rectifiers

It is a generally well-known fact that germanium or silicon monocrystal diodes are rather sensitive to thermal or voltage stresses above the normal limits.

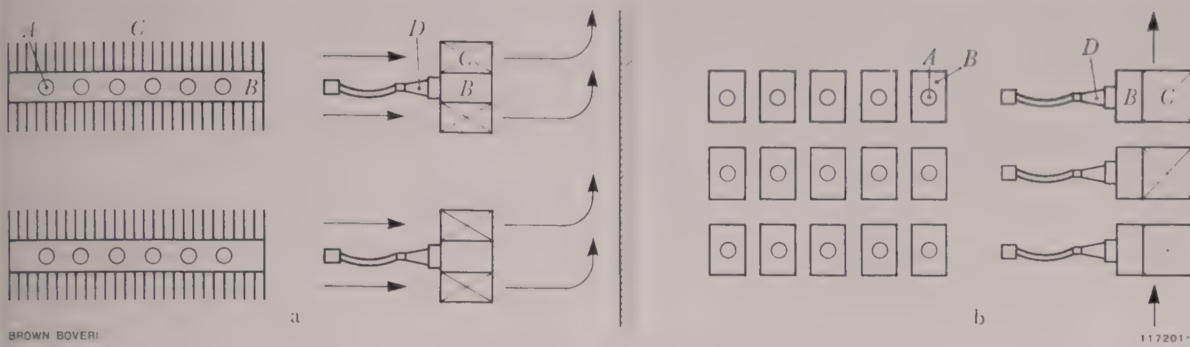


Fig. 21. – Cooling systems for semiconductor rectifiers

a: Parallel cooling b: Series cooling

A = Tapped holes for the diodes B = Body of the cooler C = Cooling fins D = Diodes

When planning the protective gear it is necessary to distinguish between two major spheres; the one comprises the operational states which occur normally, and are therefore visualized in advance. This group contains overcurrents, as described in the previous chapter, and normal overvoltages encountered in service. These stresses have been adequately dealt with in a number of publications and will therefore not be tackled here. The second group includes the stresses imposed by fault conditions. The measures taken to protect the diodes against such stresses are described on pages 181–92 of this issue.

Concluding Remarks

This article is intended to provide the engineer who has to plan semiconductor rectifier installations with the necessary assistance, as well as acquainting the user of such an installation with its technical peculiarities. The overvoltages which may be applied to the diodes from the d.c. or a.c. side must be counteracted by appropriate protective measures. On account of the heat storage capacity of the diodes being much smaller than in other conventional converters, such as mercury-arc rectifiers, for instance, it is essential to provide quick-acting protective devices to protect the diodes against current overloads. These devices include specially developed, ultra-rapid fuses, as well as the shorting switch taken over from the mechanical rectifier. For special applications d.c. circuit-breakers are employed which, to meet the requirements of semiconductor rectifier installations, have a defined arc voltage and very short break times.

	Interphase transformer	3-phase bridge	1-phase bridge
$\frac{U_{v0}}{U_{dio}}$	0·855	0·74	1·11
$\frac{U_{vm}}{U_{dio}}$	2·1	1·05	1·57
$\frac{I_t}{I_{d1}}$	0·289	0·815	1
$\frac{I_{td}}{I_{d1}}$	0·167	0·333	0·5
$\frac{P_t}{U_{dio} \cdot I_{d1}}$	1·26	1·05	1·11

U_{dio} = Ideal no-load d.c. voltage
I_{d1} = Rated direct current
U_{v0} = Secondary voltage of transformer at no-load
U_{vm} = Maximum inverse voltage
I_t = Secondary current of transformer (r.m.s.)
I_{td} = Mean value of secondary current of transformer
P_t = Mean apparent power of transformer

According to IEC publication No. 84, 1957
(Assuming the direct current is completely smoothed)

It is important to utilize the inherently small overload capacity of silicon rectifiers in certain applications, e.g. in railway traction. The use of appropriately designed overcurrent relays, whose characteristic closely conforms to that of the diode permits optimum solutions to be obtained in this respect. Having regard to the initial cost of the installation and the capitalization of the losses, it is possible to reach an optimum as regards the operating costs of silicon rectifiers. Besides the excellent efficiency of the diodes, another factor which exerts a favourable influence is that the transformer can be built for an impedance voltage of 4 to 8%, thereby ensuring an economical design of the transformer.

In any case it is a great advantage to deal separately with the various problems encountered when planning a silicon rectifier installation. From their long experience in the sphere of a.c./d.c. conversion, Brown Boveri are in a position to offer the most suitable version for any practical requirements.

(KME) K. ROLLIG

THE DESIGN OF CABINETS FOR SILICON RECTIFIERS

621.314.632:546.28

The metal cabinets in which the silicon rectifiers are housed are standardized in their principal dimensions and may be formed by various combinations of two basic units A and D, which contain the alternating and direct current elements, respectively. The present article reviews the arrangement of rectifiers with 30 or 36 diodes, or twice that number. The layout of the installation and of the rectifier unit proper, as well as the measures which have to be taken to ensure adequate ventilation and dissipation of the heat generated inside the cabinet, are dealt with in detail.

THE EXCELLENT operational results obtained with silicon rectifiers contained in metal cabinets, and the continuation of constructional development, indicated the desirability of employing solely standardized elements for these cabinets. Standardization brings great advantages because it simplifies the storage of parts, which are immediately available for delivery, thereby reducing delivery times and the price of the rectifier; on the other hand standardization makes it possible to combine up to twenty different circuit arrangements without special modifications being necessary in the design of any individual element. Furthermore, by standardizing, it becomes easier to comply with customers' wishes or special operating conditions on site. The connection to the existing electric system is also facilitated.

Constructional Aspects

The new rectifier cabinet can be assembled from various combinations of two standardized units, one of which houses the input leads and busbars of the a.c. side, as well as the switchgear, while the other contains the rectifier proper and the d.c. busbars.

In order to simplify the designation of the various combinations, the two types of unit are denoted by the letters A (for alternating) and D (for direct), respectively. The following examples give four of the principal combinations of cabinets; the numbers following the letters indicate how many silicon diodes there are in each D cabinet.

Cabinet type DA 30 or 36, contains 30 or 36 diodes in three-phase bridge connection;

Cabinet type DAD 30 or 36, contains 2×30 or 2×36 diodes in three-phase bridge connection;

Cabinet type AAD 30 or 36 for 30 or 36 diodes with interphase transformer;

Cabinet type ADDA 30 or 36 contains 2×30 or 2×36 diodes with interphase transformer.

If the cabinets are also equipped with fuses, their designation is augmented by the letter S, e.g. to DADS.

The weight of the cabinets varies with the kind of vertical busbar and the type of rectifier, amounting to about 400 kg in cabinet D and about 200 kg with A. Compared with the first designs brought out, the dimensions have been reduced in the course of the development to the following:

Cabinet A: 31 cm wide, 70 cm deep
Cabinet D: 59 cm wide, 70 cm deep

For both units the height is 1873 mm with a low plinth, or 2153 mm with a high plinth.

The cabinets type A and D have a framework of steel tubing, imparting excellent rigidity to the whole, so that it can easily support the weight of the con-

Fig. 1. – Standardized cabinet type DAD with low plinth

Fig. 2. – Standardized cabinet type ADDA with low plinth

necting bars, as well as the busbars and internal elements. This tubing also simplifies the assembly of the units with one another, and permits the doors to be closed flush with the front, thereby providing the necessary tight fit. The cabinet constructed in this manner is closed at the sides with sheet-metal panels bolted to the framework. The doors are hinged, those of the type D units being fitted with locks so that they can be opened from the front. The other cabinets can only be opened from the inside.

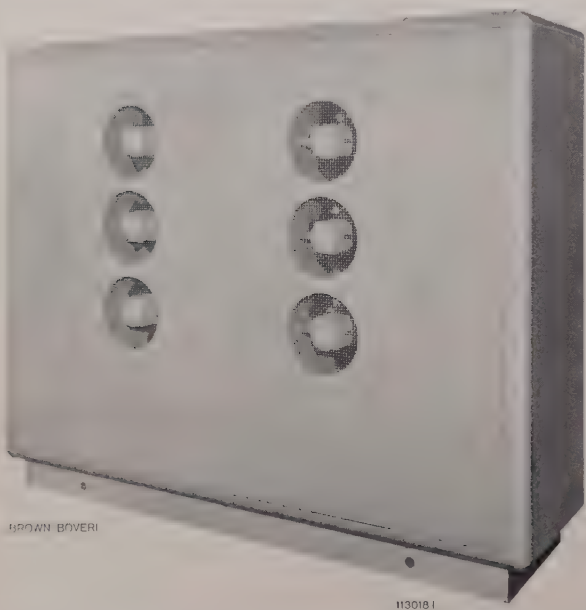


Fig. 3. – Rear view of the cabinet in Fig. 2, showing the air outlet openings

The cabinet generally rests on a plinth 133 mm high, the fresh air for cooling the diodes and busbars entering through ducting in the floor (Fig. 1, 2, 3). If the air is drawn in from the room in which the cabinet stands, it must be on a higher plinth (400 mm high) provided with the necessary louvres (see Fig. 4). One of the doors of every cabinet carries the main operating button, with indicator lamps for the shorting switch, the fans and the supervisory gear; these lamps are arranged according to a system of coordinates and light up when one of the diodes or an auxiliary circuit is defective.

Internal Arrangement

The rectifier blocks and the associated vertical busbars are so designed that they can be arranged to suit the system of connection desired. Fig. 5 and 6 depict two typical circuit arrangements for cabinets

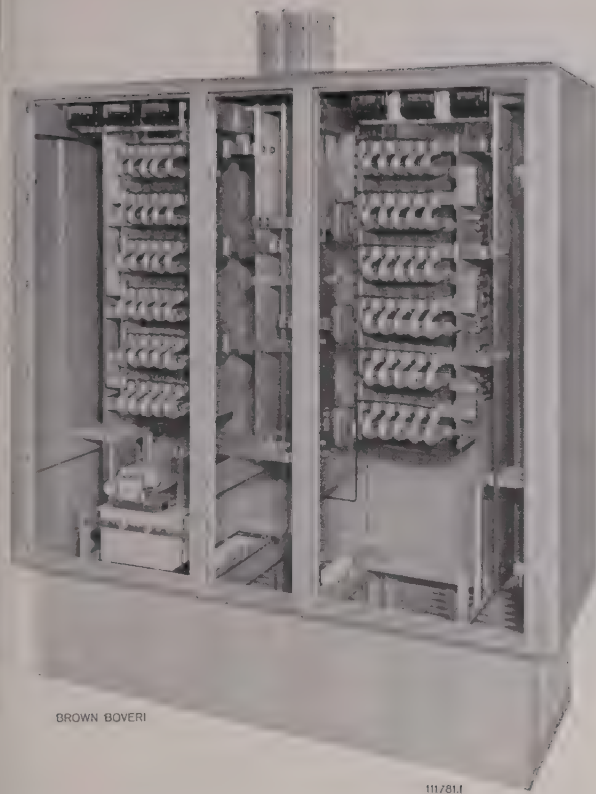


Fig. 4. – Standardized cabinet type DAD 30 with high plinth, doors removed

The connections to the vertical main busbars are at the top of the cabinet.

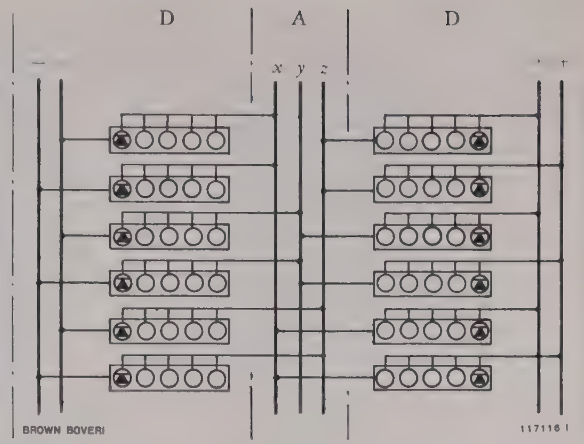


Fig. 5. – Circuit diagram of a cabinet type DAD for three-phase bridge connection with parallel tiers of diodes

Direct current	6000 A
Voltage	500 V
D.C. power	3000 kW

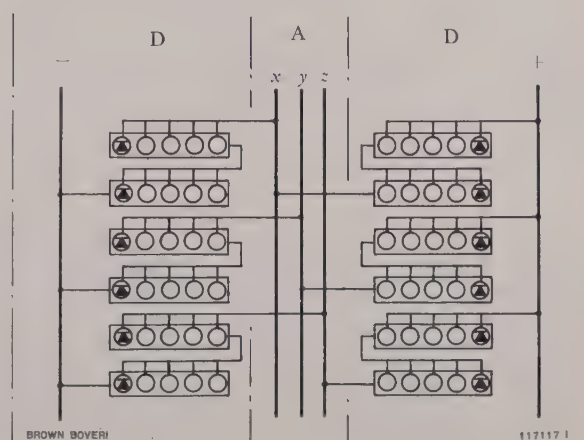


Fig. 6. – Circuit diagram of a cabinet type DAD for bridge connection with parallel groups of two tiers in series

Direct current	3000 A
Voltage	1000 V
D.C. power	3000 kW

type DAD, with bridge-connected rectifiers, one with the tiers of diodes in parallel, the other with tiers in series. In the latter case it is possible to obtain rectifier voltages of up to 1000 V. The rectifier blocks, i.e. one in each of the type D units, are organized in six tiers, as can be seen in the illustrations, each with five or six diodes in parallel; with the aid of crossbars these tiers are connected to the vertical busbars. This arrangement is clearly visible in Fig. 8.

The a.c. and d.c. bars are mounted in three separate sections, according to the strength of the current. The d.c. bars may be mounted singly or in pairs, their connection to the external system—as with the a.c. bars—being possible either at the top or bottom of the cabinet. Each cabinet type D also accommodates the equipment protecting the fan motors and the supply for the indicator lamps; these elements are mounted just below the roof of the cabinet.

Ventilation of the Rectifier Cabinets

The losses of a silicon diode amount to about 250 W, which for a block of 30 diodes adds up to 7500 W, to which the losses of the busbars and any fuses provided must also be added. Hence for one rectifier block in a type D cabinet the losses can

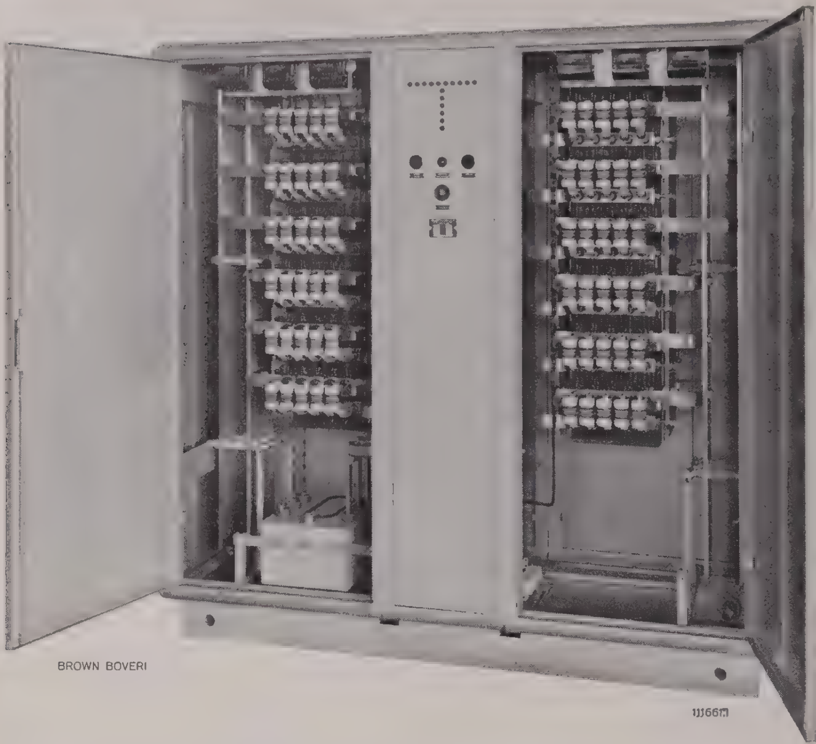


Fig. 7. – Cabinet type DADS 30

The vertical busbars are connected to the rectifier blocks by crossbars.

amount to about 10 kW. Various methods are available for dissipating these losses. As a result of the excellent experience gained over many years with the cooling of mercury-arc rectifiers, air cooling was selected as being the simplest method for silicon rectifiers. In contrast to water cooling, it does not

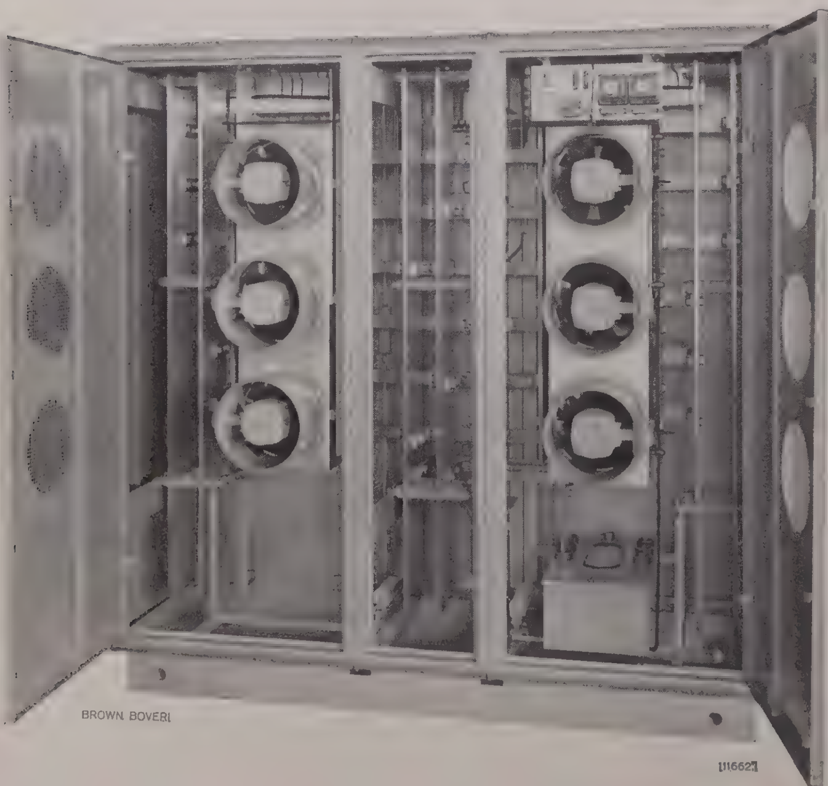


Fig. 8. – Fans and vertical busbars in a cabinet type DAD

involve any special insulation problems. The air cools not only the diodes, but also the other elements in the cabinet, such as the busbars, fuses, and so on. Following exhaustive tests, a very small cooling attachment was devised for the diodes, providing maximum cooling with a minimum of air. It is designed as a copper block on to which the diode is screwed, and has holes at the sides through which the assembly is attached to the busbars. The block has fins, spaced so that dust cannot accumulate. The turbulence of the current of air is enhanced by small ribs on the fins (Fig. 9). Parallel diodes are fixed to a common cooling attachment, thereby avoiding joints and difficulties with contact resistance. Depending on the number of diodes, the single-piece coolers may be of different lengths. For instance, the dimensions and weights of coolers for one, five and six diodes are as follows:

1 diode: 12 cm high, 5 cm wide, 5 cm long, 1·05 kg in weight

5 diodes: 12 cm high, 5 cm wide, 25 cm long, 5·25 kg in weight

6 diodes: 12 cm high, 5 cm wide, 30 cm long, 6·3 kg in weight

For ventilation of the 30 or 36 diodes of a type D cabinet the cooling elements are mounted one above the other in the fan housing, in the rear of which is the group of three fans, each of which ventilates ten or twelve diodes. The advantage of this method of ventilation is that all the coolers are traversed in parallel by the current of air, and consequently each diode assumes the same temperature. In the standardized cabinets the enclosure through which the air flows is of insulating material and simultaneously forms the support for the rectifier block. The air flowing through the coolers is finally forced out of the cabinet through round openings at the rear (Fig. 3). The warm air may be used to heat the room. Supposing the inlet temperature of the air is 40 °C, it emerges from the cabinet at about 25 °C higher. If the inlet temperature exceeds 40 °C, or if the atmosphere contains aggressive vapours, it is necessary to provide

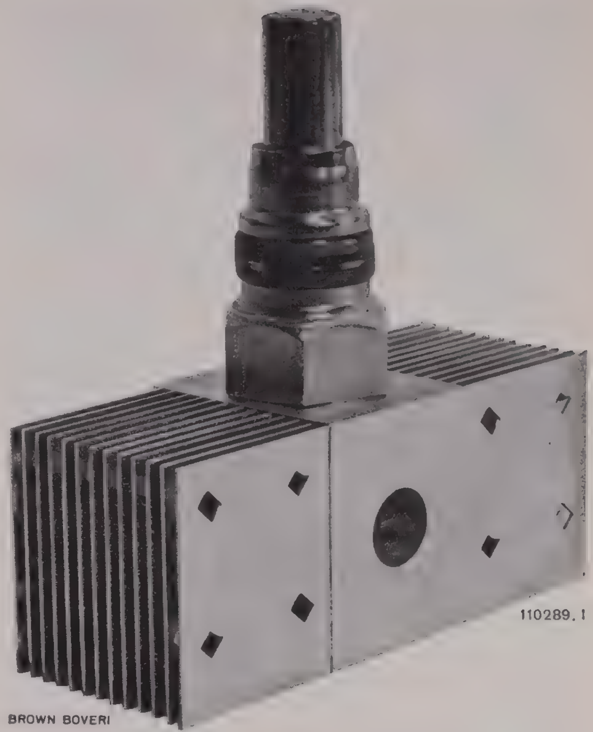


Fig. 9. – Part of a cooler with associated diode

closed-circuit cooling with a heat exchanger between the air and the cooling water circuit, a small amount of fresh air being drawn in through a filter to create a slight excess pressure inside the cabinet, and to compensate for loss of air. The heat exchanger, which is accommodated in the lower part of the type D unit, allows the rectifier to operate at an ambient temperature of 40–50 °C and with a maximum water temperature of 30 °C. With a flow of 15 litres/min of water the temperature of the air can be reduced by about 25 °C.

Rectifier Block

This, of course, is the most important part of the equipment in the cabinet type D. It is formed of silicon diodes, attached to the coolers described above. Owing to the small diameter of the fuse developed by Brown Boveri in collaboration with Schurter AG, Lucerne, the dimensions of the coolers are also remarkably small. The design of these fuses offers

Fig. 10. – Rectifier block with tiers, each consisting of five parallel diodes

several advantages, in that they only create a very slight resistance to the flow of current and, as a result of a well-planned arrangement with flexible connections, establish the direct link between the diodes and the crossbars. With this arrangement the fuses can be easily renewed when necessary, or defective diodes replaced.

The special design of the rectifier block simplifies the standardization of its design. Cathodes and anodes can be independently connected to the a.c. or d.c. busbars by means of cross-connections. It is also possible to connect the tiers of five or six diodes in parallel or series. The crossbars used for connecting the vertical main busbars with the anodes are such that they can also carry the devices for indicating when diodes or fuses are defective. The rectifier block also contains the protective gear. Some idea of the layout of the rectifier block is given by Fig. 10.

Shorting Switch

The task of this switch is to protect the diodes against overcurrents on the d.c. side, as explained in the article beginning on page 228. It operates on the same principle as the shorting switch in the mechanical rectifier, but its constructional design has been adapted to the special conditions of silicon rectifiers. In the type A cabinet it is attached to the a.c. busbars, immediately adjacent to the connections from the rectifier transformer. It can be operated by a number of tripping circuits, while resetting is performed automatically by a motor, or on traction vehicles by compressed air.

(KME) C. BEAU

RECTIFIER TRANSFORMERS FOR HEAVY CURRENTS

621.314.1

Rectifier transformers are generally obliged to fulfil more varied and more stringent requirements than ordinary transformers in power systems. Apart from this there is the trend towards higher type ratings for the individual transformers, owing to the need to provide capacity for future expansion in newly erected installations. If the plants concerned are engaged on electrolysis or similar processes, the d.c. voltage frequently does not increase to the same extent; indeed it is often reduced, and this leads to an appreciable growth in the secondary current of the transformer, posing some very special problems for the transformer designer. The present article, concentrating on these special conditions, deals with the various questions arising during planning, calculation and the design of such transformers.

Planning

THE VERY NATURE of its duties, i.e. operation in conjunction with rectifier elements to convert alternating current into direct current, gives some idea of the special requirements which a rectifier transformer has to fulfil. Thus the d.c. power consumption, on the one hand, and the power available on the a.c. side largely determine the *pulse number* of the installation. It is well known that this number governs the harmonic content of the primary currents and secondary voltages. If the supply voltage is truly sinusoidal, and under ideal commutation conditions,[1] the primary currents contain the harmonics [1] [2] given by

$$n = k \cdot m \pm 1$$

having an amplitude of $a = (100/n)$ % of the fundamental, where $k = 1, 2, 3 \ldots$ and m is the pulse number. Furthermore, the secondary d.c. voltage contains the harmonics given by $n = k \cdot m$ with a r.m.s. value of $a = \frac{\sqrt{2} \cdot 100}{n^2 - 1}$ % of the d.c. voltage. The occurrence of harmonics and their magnitude are thus governed solely by the selected pulse number. The nature of the circuit has nothing to do with the matter. Increasing the pulse number improves the ratio between the r.m.s. value of the fundamental of the primary current and its total r.m.s. value, i.e. the current distortion becomes less. This is related to the power factor by the well-known formula

$$\lambda = v \cos \varphi$$

in which λ is the power factor, v the distortion and $\cos \varphi$ the displacement factor. With increasing pulse number the inherent distortion in the primary voltage also improves. This relationship cannot be entered into here, but it is amply covered by the literature [3]. However, it may be pointed out that merely reducing the distortion in the primary current and voltage, for its own sake, does not justify the extra outlay for a rectifier installation with a higher pulse number. The voltage distortion only becomes important when the ratio between the connected d.c. load and the short-circuit power of the supply system is relatively large. It will thus be necessary to check from one case to another, what pulse number has to be selected, according to the ratio of the d.c. load to the available power, at the same time having regard to a solution which is technically feasible at an acceptable price.

In addition there is the circuitry to be considered. From the variety of possible arrangements the two which have proved ideal for heavy currents are the

[1] Disregarding leakage and magnetizing current of the transformer, with no voltage drops in reactors, and with fully smoothed d.c.

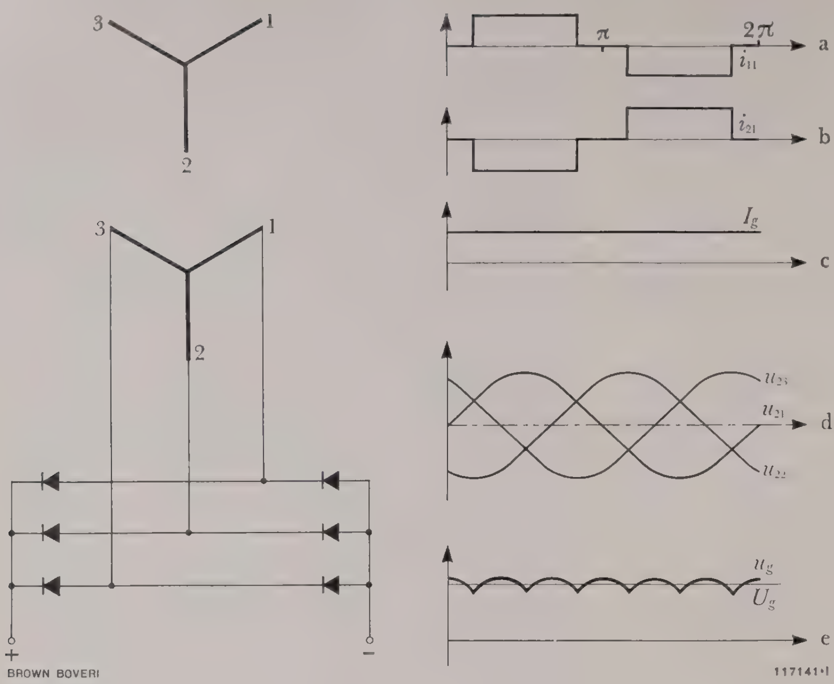


Fig. 1. – Connection, and diagrams of voltage and current of a hexapulse bridge circuit

a: Primary current i_{11} in phase 1
b: Secondary current i_{21} in phase 1
c: Direct current I_g
d: Secondary voltages u_{21}, u_{22}, u_{23}
e: D.C. voltages u_g, U_g

three-phase bridge circuit and the *interphase transformer (or double-star)* circuit. Subsequent remarks will be confined to these two circuits.

The simple bridge circuit with its hexapulse repercussions on the supply system can be obtained with any normal three-phase transformer connection (Fig. 1). Generally speaking the r.m.s. value of the current is

$$I = \sqrt{\frac{1}{T} \cdot \int_0^T i^2 \cdot \mathrm{d}t}$$

and, with ideal commutation conditions in the present case on the secondary side of the transformer

$$I_2 = \sqrt{2}\, I_g/\sqrt{3}$$

where I_g is the total direct current.

If the transformer has a ratio of 1:1, the same value is obtained for the primary current. The primary and secondary r.m.s. powers are equal and the capacity of the transformer is well utilized.

In the case of the hexapulse interphase transformer circuit (Fig. 2) the conditions are rather different. Assuming the same circumstances as before, the secondary phase current is given by

$$I_2 = \frac{1}{2 \cdot \sqrt{3}} \cdot I_g$$

while the primary current is

$$I_1 = \frac{\sqrt{2}}{2 \cdot \sqrt{3}} \cdot I_g$$

From these formulae it will be recognized that the primary current is $\sqrt{2}$ times larger than the secondary phase current. Doubling the number of phases on the secondary side implies increasing the secondary type rating compared with that of the primary by a factor of $\sqrt{2}$, i.e. the capacity of the windings is not utilized so well. Which of the two circuits should be preferred in a particular case will be governed not only by the direct current and d.c. voltage, but also by the type of rectifier elements employed. The ability to execute the design of the transformer will also have a certain amount of influence on the choice of circuit. Consider, for example, a twelve-pulse bridge circuit with a single transformer for a low secondary voltage (Fig. 3).

If facilities exist for the numbers of turns of the secondary windings to be in the ratio $1:\sqrt{3}$ (e.g. 4:7), preference will be given to arrangement I; if

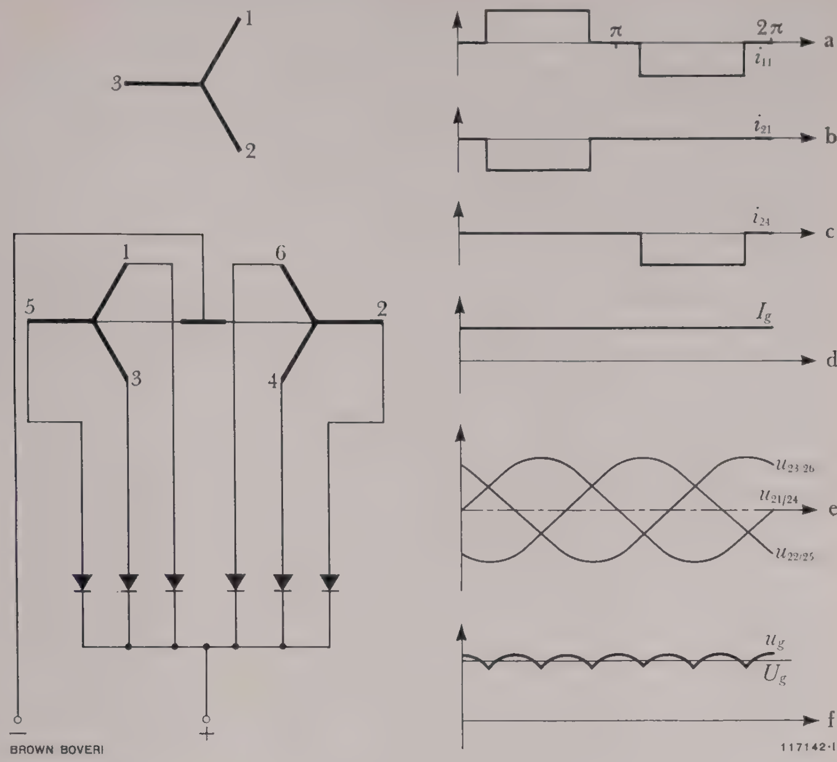


Fig. 2. – Connection, and diagrams of voltage and current of a hexapulse interphase transformer circuit

a: Primary current i_{11} in phase 1
b: Secondary current i_{21} in phase 1
c: Secondary current i_{24} in phase 4
d: Direct current I_g
e: Secondary voltages of phases 1–6
f: D.C. voltages u_g, U_g

this is not possible, it will be necessary to adopt either II or III, in which case the iron frame has to have an intermediate yoke (I in Fig. 4) to absorb the flux difference $\Delta\Phi$ between the two mutually displaced primary systems. In the case in point the primary systems Φ_1 and Φ_2 are displaced by 30°, i.e. the flux difference amounts to 52% (approx.) of the main flux (see II in Fig. 4).

With extremely heavy currents and low voltages on the secondary side it may perhaps be necessary to subdivide the capacity between a number of transformer units. If the choice of connection on the

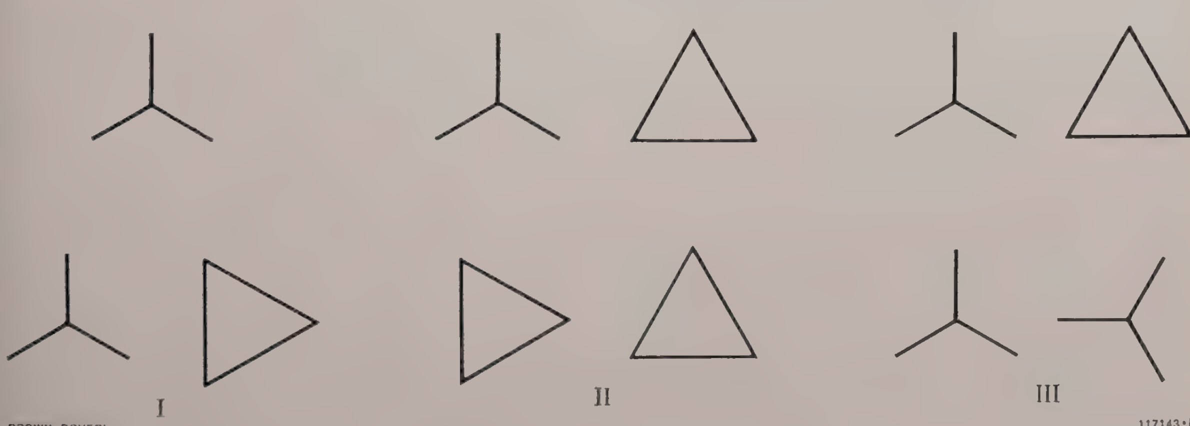


Fig. 3. – Possible twelve-pulse bridge connections using a single transformer unit

I: Secondary in star-delta, turns ratio $1:\sqrt{3}$
II: Primary in star-delta, iron frame with intermediate yoke
III: As in II, but secondary in star

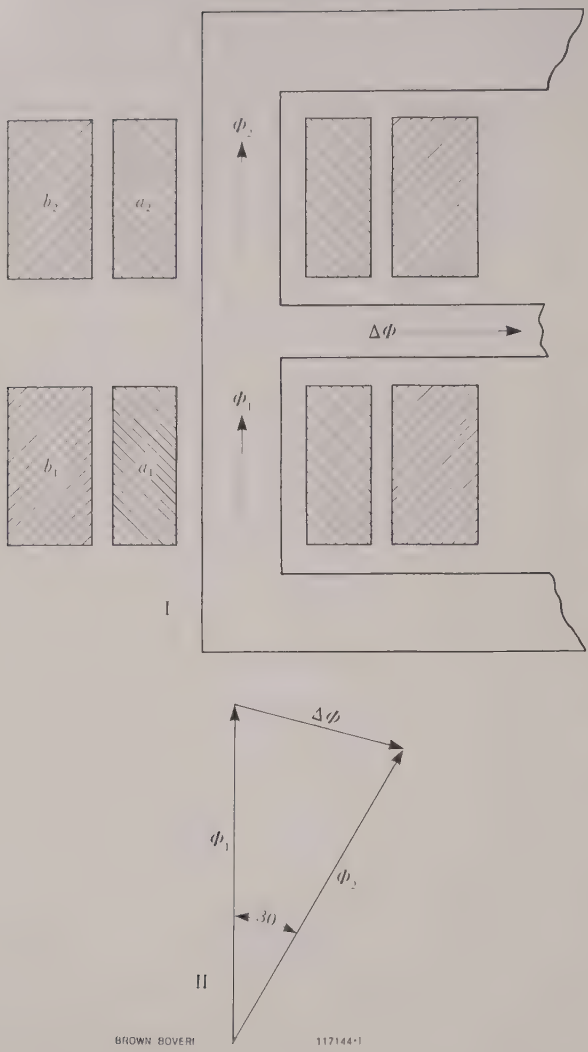


Fig. 4. – Rectifier transformer with intermediate yoke for twelve-pulse bridge circuit

I: Iron frame   II: Flux vector diagram

a_1 = Primary winding, deck 1
a_2 = Primary winding, deck 2
b_1 = Secondary winding, deck 1
b_2 = Secondary winding, deck 2

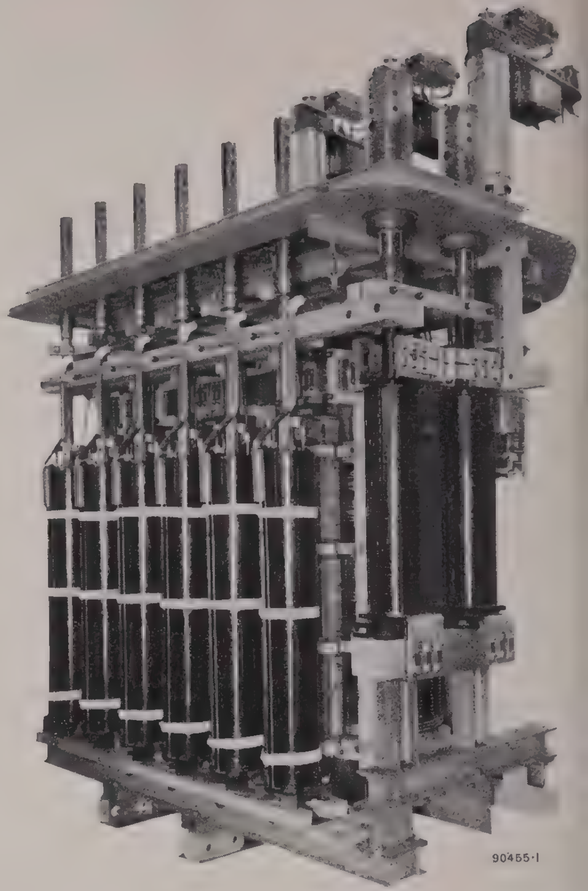


Fig. 5. – Variable-voltage transformer used with a mechanical rectifier

Showing the built-in comreactors and interphase transformer

primary side may be made freely, the star connection will be chosen in most cases for high voltages and the delta for heavy currents.

The transformers under discussion are mostly employed in electrolysis or similar plants. Since these plants have to operate with varying numbers of baths, the secondary voltage usually has to be variable over quite a wide range, at constant secondary current. The secondary voltage can be set approximately by means of a tap changer—usually automatically controlled on the primary side of the transformer—because it is technically extremely difficult, and quite uneconomical to switch the heavy secondary currents direct. With very small numbers of turns, moreover, there is no longer any possibility of tapping off voltages smaller than that of a single turn. Even reconnection of the secondary terminals to provide half the normal voltage is hardly advisable.

For the fine setting of the voltage between two tappings of the tap changer, in semiconductor rectifier installations, transductor chokes are used to vary the premagnetization of the iron core of the control reactors. Like the interphase transformers in the double-star circuit and the comreactors used with the mechanical rectifier, these reactors are housed in the

transformer tank (Fig. 5). Here the slimline design introduced by Brown Boveri for these reactors—featuring minimum space requirements and simple wiring—has proved particularly successful [4]. They may be designed as single or double reactors, according to the particular circumstances.[2]

Primary control can be effected in a number of ways, the most expedient being chosen for each set of circumstances. The simplest method is a tap changer connected to the star-point of the transformer. The outlay is considerably greater with a delta primary winding since a phase switch has to be employed. Naturally, as the range of variation is extended, the type rating of the transformer has to be increased, and this pushes up the price. For high primary voltages and when very wide ranges of variation are required, it may be preferable to change to a separate regulating transformer, which is usually connected as an auto-transformer and may be conveniently accommodated in the transformer tank. Compared with a separately mounted regulating transformer, this arrangement not only saves considerable space, it also reduces the risk of a short circuit between the auto-transformer and the rectifier transformer, as well as obviating the need for expensive short-circuit protection gear. (Owing to their low impedance voltage, especially when the ratio is small, auto-transformers are generally not short-circuit-proof on their own.) If a number of main transformers are installed, it is usually sufficient to provide only one series transformer for voltage control; in this case the problem of short circuit just referred to must be given due attention.

The choice of the pulse number mentioned at the beginning of the article can be put into effect by different transformer connections. For twelve-pulse operation star-delta connection is probably the most convenient; it merely requires an intermediate yoke if it is to be accommodated in a single transformer and arranged on the primary side. There is no increase in the amount of power to be absorbed by the winding (Fig. 4 and 6).

[2] In mechanical rectifiers the fine adjustment of the voltage is effected by adjustment of the contact timing [5].

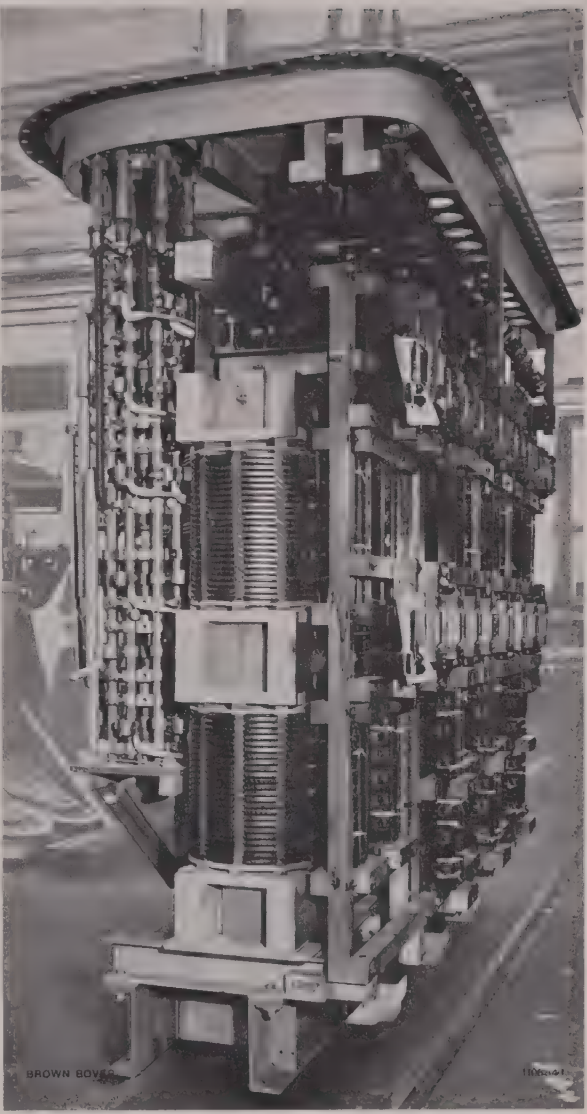


Fig. 6. – Rectifier transformer with intermediate yoke for a twelve-pulse circuit

If this connection is impracticable for any reason or if a higher pulse number is specified, the transformer may be equipped with *phase-shifting windings*; these may be housed in the rectifier transformer, in the regulating auto-transformer, if provided, or in a special phase-shifting transformer which can be combined with the main transformer. These windings shift the secondary voltage vector relative to the primary vector by the phase-shift angle, which can be selected according to the desired pulse number and the number of transformer units.

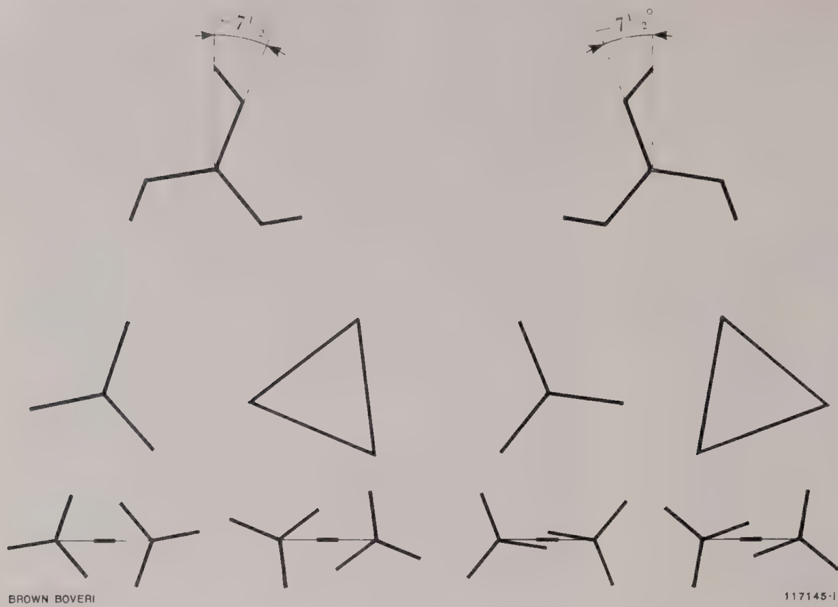


Fig. 7.–Twentyfour-pulse interphase transformer circuit employing a pair of star-delta main transformers with intermediate yoke and built-in phase-shift transformer

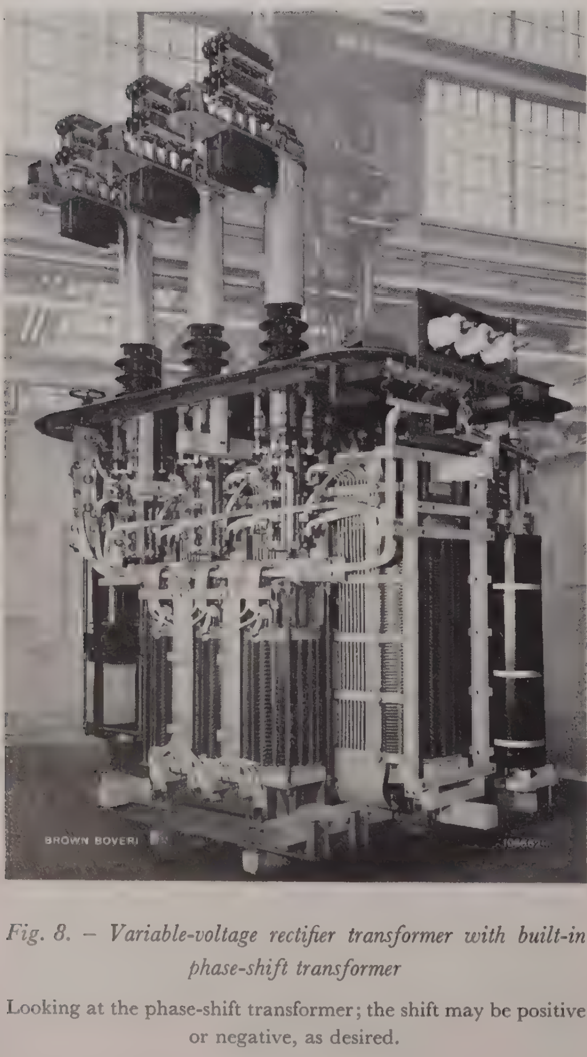


Fig. 8. – Variable-voltage rectifier transformer with built-in phase-shift transformer

Looking at the phase-shift transformer; the shift may be positive or negative, as desired.

The shift is effected by dividing the appropriate winding in two, as in the zig-zag connection. The two parts of the winding, their size being determined by the specified angular shift, are mounted on separate limbs of the core. In the following example a connection is described for a pulse number of 24, in which two transformer units each contain a built-in phase-shift transformer (Fig. 7). The advantage of this arrangement is that the two transformer units are identical from the constructional aspect, and only differ in the interconnection of the two parts of the windings of the phase-shifting auto-transformer. In most cases it requires only a few quick manipulations to convert the shift of the one transformer into that of the other (Fig. 8). The larger the angular shift is made, the larger the type rating of the transformer has to be.

With several parallel rectifiers having the same pulse number it is unnecessary to provide the same number of parallel transformers, so that they are completely decoupled. A single transformer of multi-deck design will suffice, provided the clearance between individual decks is large enough to prevent one from influencing another.

In installations of this kind the efficiency of the transformer is a very important factor, in that the value stipulated by the customer for the capitaliza-

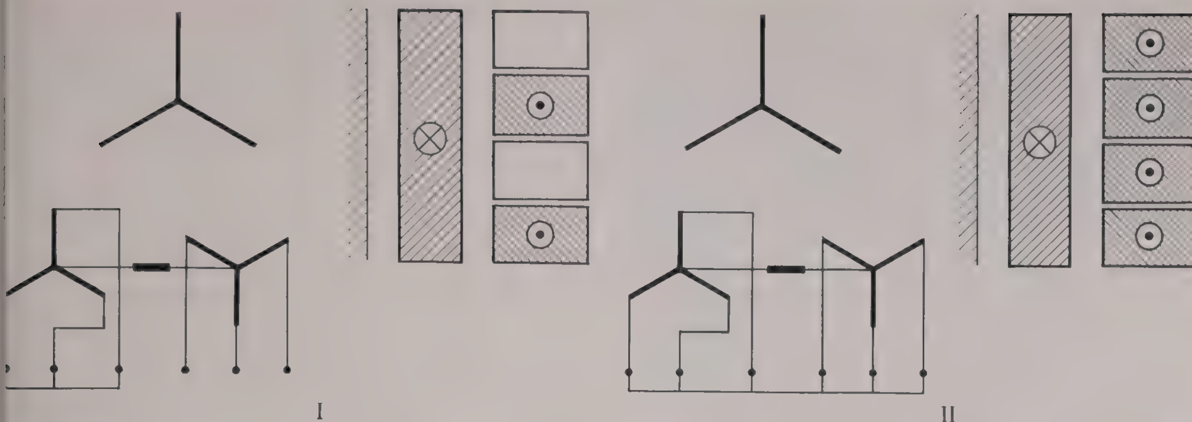


Fig. 9. – Measurement of impedance voltage in an interphase transformer circuit, and the corresponding magnetizing force (ampere-turns per cm)

I: Only one three-phase star short-circuited II: Six-phase short circuit

tion of losses must be compared with the cost of the transformer in every case. Usually it is worth while accepting the somewhat higher initial cost of an installation with a better efficiency.

All the points discussed above must be weighed against one another in order to arrive at the optimum solution.

Calculation

When designing a rectifier transformer there are a number of points which must be considered in addition to those for a normal transformer for power distribution. Firstly, in a transformer with several secondary windings, it is important to ensure that these all receive the same no-load voltage. This is not always easy to achieve, especially in heavy-current l.v. installations; take, for example, the star-delta secondary which, as mentioned above, must have a turns ratio of $1:\sqrt{3}$. For this it would be necessary to select an iron cross-section whose inductance is not only fully utilized, but which corresponds approximately to the type rating of the transformer. For dependable operation, however, not only the no-load voltages but also the full-load voltages of the secondary windings should be equal, i.e. the latter must possess the same impedance voltage relative to the primary winding. If these impedance voltages differ from one another, this leads to unequal current consumption by the systems, and additional harmonics in the direct current. Furthermore, with the interphase transformer circuit the current distribution becomes unbalanced. Equal impedance voltages can be obtained by appropriate arrangement of the windings.

It is quite a simple matter to calculate the impedance voltage for star or delta connection of the secondary, apart from the additional impedance of heavy-current leads. For interphase transformer circuits, combined star-delta connections on the secondary side or with the multi-deck arrangement, it is first necessary to establish to what power and type of short circuit the impedance voltage must be related. For instance, in various specifications for the hexapulse interphase transformer circuit the impedance voltage is stipulated for a short circuit on only one three-phase star, the full rated current flowing on the primary side (I in Fig. 9). In this case the impedance voltage can only be determined exactly after exhaustive calculation, because with certain winding arrangements the magnetic force (ampere turns per cm) of the secondary winding is interrupted by the second secondary star which is not short-circuited, thus leading to inhomogeneous stray fields. A six-phase short circuit is far better, since all windings are then involved in the short and the magnetizing force

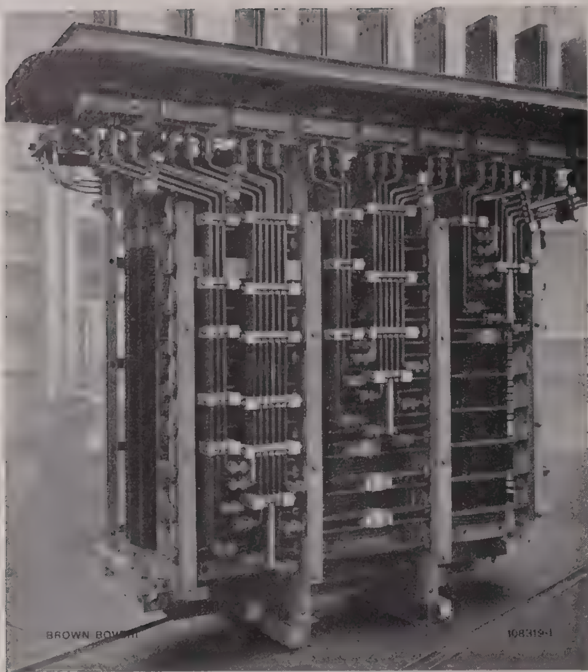


Fig. 10. – Transformer of a semiconductor rectifier installation

Showing the secondary current bars

is homogeneous (II in Fig. 9). Analogous considerations apply to units in which several systems are mounted on a single iron frame.

With existing phase-shift windings the currents on the primary side are out-of-phase with those on the secondary side. The algebraic sum of the fluxes on the secondary side is not equal to that on the primary side. This produces a supplementary leakage system, which increases the overall impedance of the transformer.

In the transformers being considered, the output bars needed to carry the heavy current make quite a large contribution to the overall impedance of the transformer (Fig. 10). However, it is not always easy to calculate the extent of this contribution, and values gained by experience have frequently to be relied upon.

Under known supply conditions the impedance voltage determines the magnitude of the short-circuit currents. If the damping effect of the system impedance is neglected to begin with in an ordinary transformer, having an impedance voltage of 6–8% and a surge factor of 1·6, the asymmetric value of the short-circuit surge current may amount to $\frac{1{\cdot}6 \times \sqrt{2} \times 100}{(6 \text{ to } 8)}$ = between 38 and 28 times the rated current. In rectifier transformers this figure can be still larger. For example, in an interphase transformer circuit, with a three-phase short circuit, it is increased by the factor $\sqrt{2}$ on the secondary side (only one system bears the brunt of the full short circuit). In the event of a backfire, which at first represents a double-pole short circuit for the transformer, the current can continue to rise in one limb; similarly with a reverse current from the d.c. side. The two latter possibilities of current increases, however, do not concern the present investigations because, for semiconductor rectifier installations, Brown Boveri use either a quick-acting shorting switch or fuses, with the result that in a few milliseconds either the transformer secondary side is converted into a short circuit involving the whole system—e.g. into a six-phase short in a hexapulse interphase transformer circuit—or it is disconnected altogether.

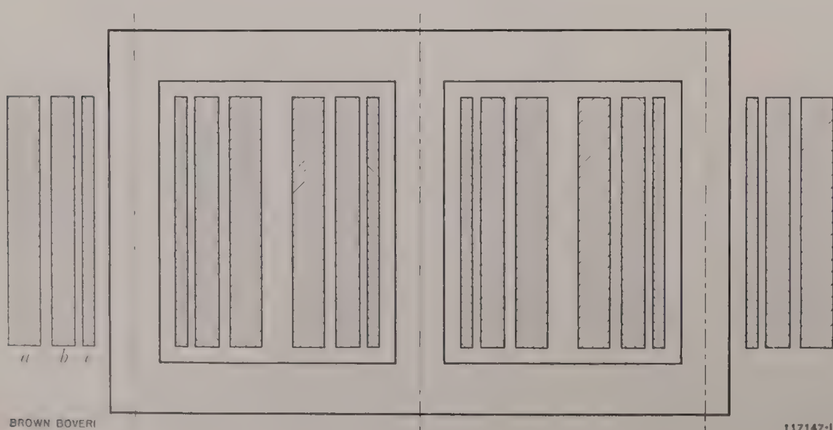


Fig. 11. – Principle of the construction of a variable-voltage rectifier transformer

a = Secondary (l.v.) winding
b = Main primary (h.v.) winding
c = Primary regulating winding

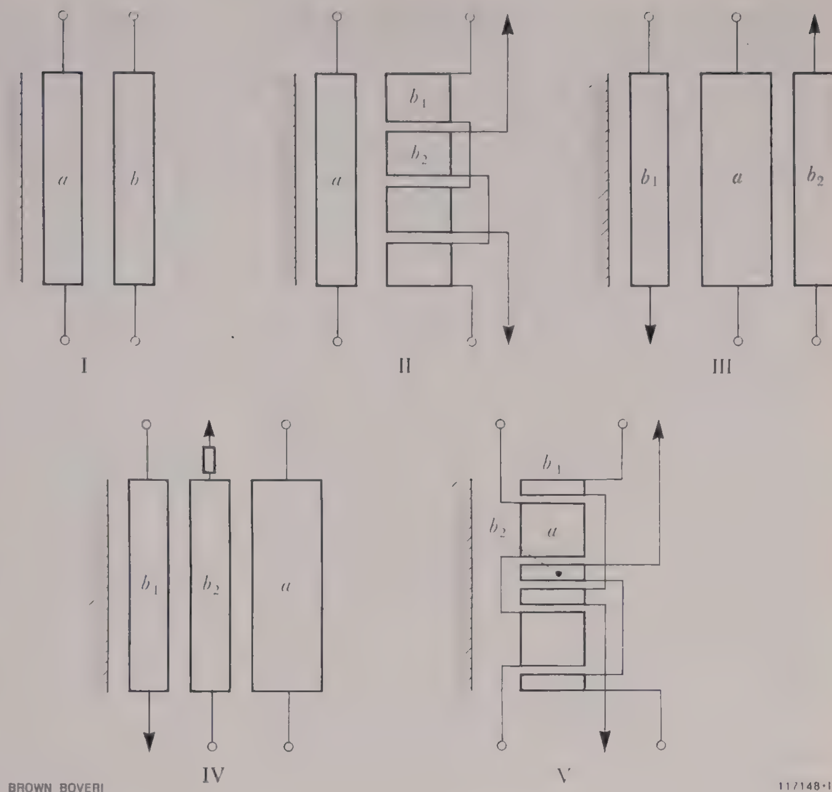


Fig. 12. – Alternative winding arrangements

I: Simple bridge circuit

II: Hexapulse interphase transformer circuit, with interleaved secondaries

III: As II, but with double-concentric arrangement of the secondary systems

IV: As II, but with the two secondary systems on the inside. The system with the smaller stray field towards the primary side is augmented by a reactor, so that both systems have the same impedance voltage

V: As II, but with disc winding

a = Primary (h.v.) windings
b, b_1, b_2 = Secondary (l.v.) windings

Having regard to the impedance of the supply system, and any other impedances which may be present, the possible short-circuit currents must be calculated as accurately as possible, in any case, since they determine the magnitude of the mechanical stresses in the winding.[3] It is common knowledge that the forces vary with the square of the current. Now since the short-circuit currents cannot be limited more than a certain amount—it would be uneconomical to increase the impedance voltage beyond a certain figure—and since short circuits are not completely avoidable yet in rectifier installations, special precautions have to be taken to cope with the forces in the transformer. Firstly an effort should be made to reduce the short-circuit forces by choosing an appropriate winding arrangement. In any case axial asymmetry must be avoided, especially in double and multiple systems, but also with tappings, and so on; at the same time it is important to ensure good current distribution.

[3] Owing to the rapid interruption of the transformer, the thermal stresses are insignificant.

Owing to the heavy secondary currents, the arrangement of the winding should be as simple as possible. With a hexapulse bridge circuit this is quite easy, in that, provided the primary voltage is not unduly high, the h.v. winding can be innermost, nearest to the iron, while the heavy-current secondary can be on the outside and subdivided into a number of parallel coils (Fig. 11). When the number of turns is extremely small, the secondary winding may even take the form of a single or multi-turn cylinder of sheet-metal which, at high primary voltages, can also be placed on the inside against the iron frame. Above all, in the interphase transformer circuit, the aim should be to place the secondary winding as near the iron frame as possible and so obtain a small diameter, because it has the larger type rating and is therefore the heavier winding. Some of the most important winding arrangements will now be briefly described.

Referring to Fig. 12, sketch I shows the arrangement for a simple bridge circuit; the design is the same as for an ordinary transformer. Sketches II to V

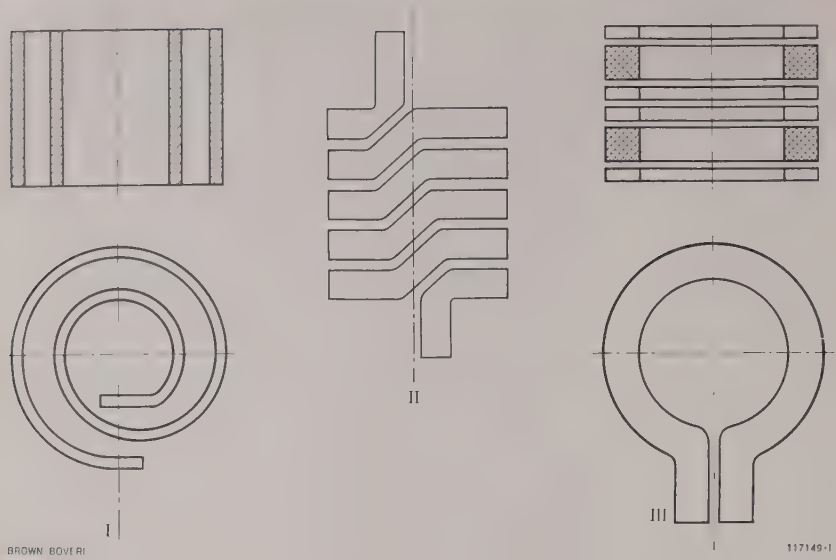


Fig. 13. – Designs of secondary windings

I = Sheet-metal cylinder winding with two turns

II = Several pieces of copper joined together

III = Disc winding with one sheet-metal turn

show possible arrangements for a hexapulse interphase transformer circuit. With the arrangement in II the two secondary systems are interwound and have a good mutual coupling. The difficulty of calculating the impedance voltage with this layout was mentioned earlier. In the system with double-concentric layout (III) the same impedance voltage with reference to a three-phase short circuit is obtained in the two systems by selecting different clearances from the h.v. winding. With a six-phase short circuit the impedance voltage drops by more than half, while the short-circuit current rises accordingly. The arrangement with the two secondaries on the inside (IV) is very simple, but to maintain equal impedance it necessitates the provision of an additional reactor, which can be accommodated in the same tank as the transformer. Sketch V shows another possible arrangement in the form of a disc winding.

Fig. 14. – Heavy-current secondary winding

Formed as a sheet-metal cylinder with several turns.

Some Constructional Aspects

Although the mechanical stresses in a transformer are quite small in normal operation—proportional to the square of the current—in a rectifier transformer their effect may be completely different, owing to the non-sinusoidal waveform of the current, resulting in the winding assembly working loose after a long period in service. In addition there is the risk of short circuits covered in the foregoing. For these reasons special constructional precautions have to be taken with all rectifier transformers.

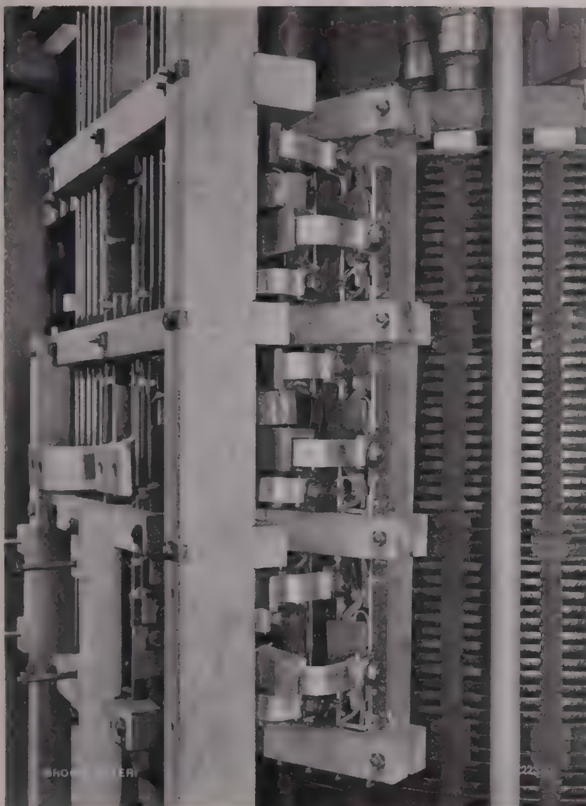


Fig. 15. – Arrangement of the secondary current connections of a rectifier transformer

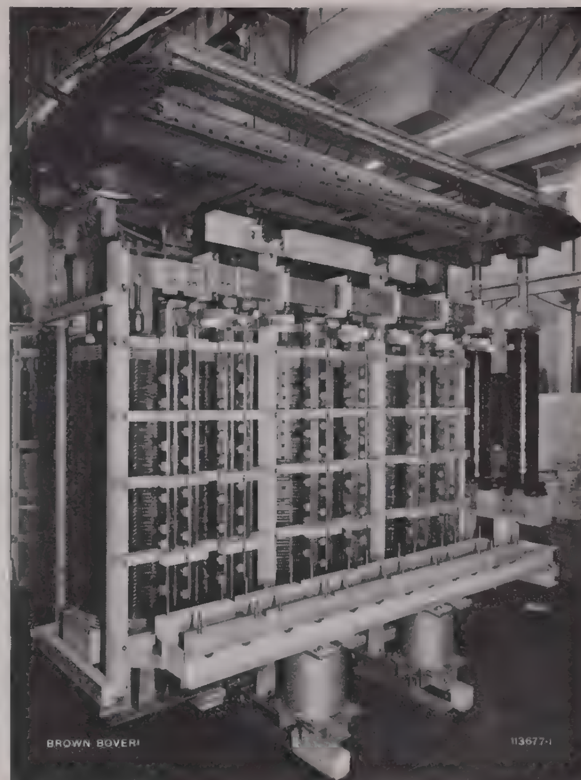
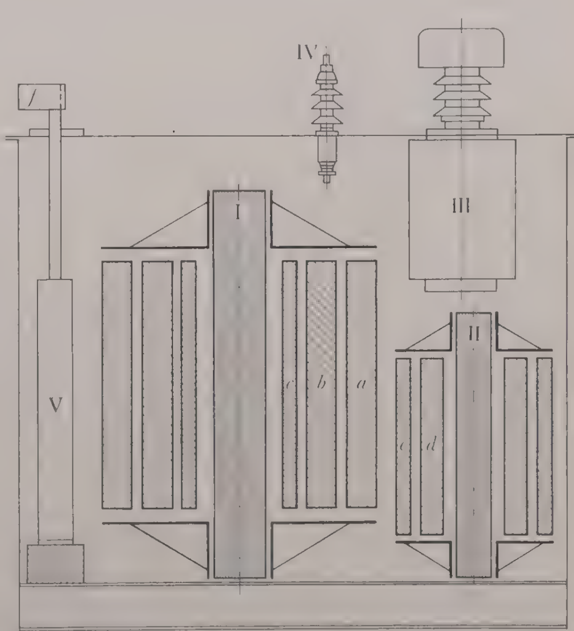


Fig. 16. – Rectifier transformer

Showing the secondary connections and the supporting bracket for the reactors still to be assembled.

Following careful drying and artificial ageing of the windings, they are equipped with a strong supporting and pressing assembly. The design of the latter must be such that, even after years of service, it must still exert the same pressure on the windings and help them to retain their full rigidity during every short circuit which occurs. If sheet-metal windings are used (Fig. 13 and 14), they may be wound from one or more concentric turns of thin copper



I: Main transformer
  a = Secondary winding
  b = Main primary winding
  c = Regulating primary winding
II: Phase-shift transformer
  d = Main winding
  e = Phase-shift winding
III: Tap changer
IV: Primary terminal
V: Control reactors
  f = Heavy-current secondary terminals

Fig. 17. – Principle of the design of a transformer for a semiconductor rectifier installation, showing the associated phase-shift transformer, tap changer and control reactors

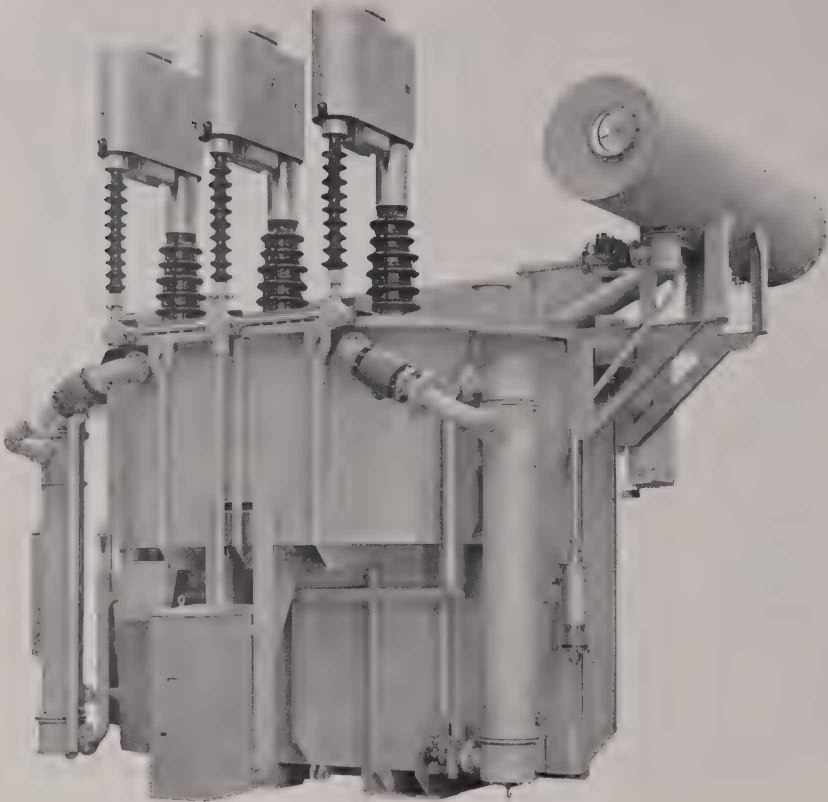


Fig. 18. – Variable-voltage heavy-current rectifier transformer

External view showing tap changer, oil conservator and Buchholz relay. The secondary connections are enclosed for transport.

Fig. 19. – Heavy-current rectifier transformer

Showing the separate radiator bank, on which are mounted the oil conservator and Buchholz protection.

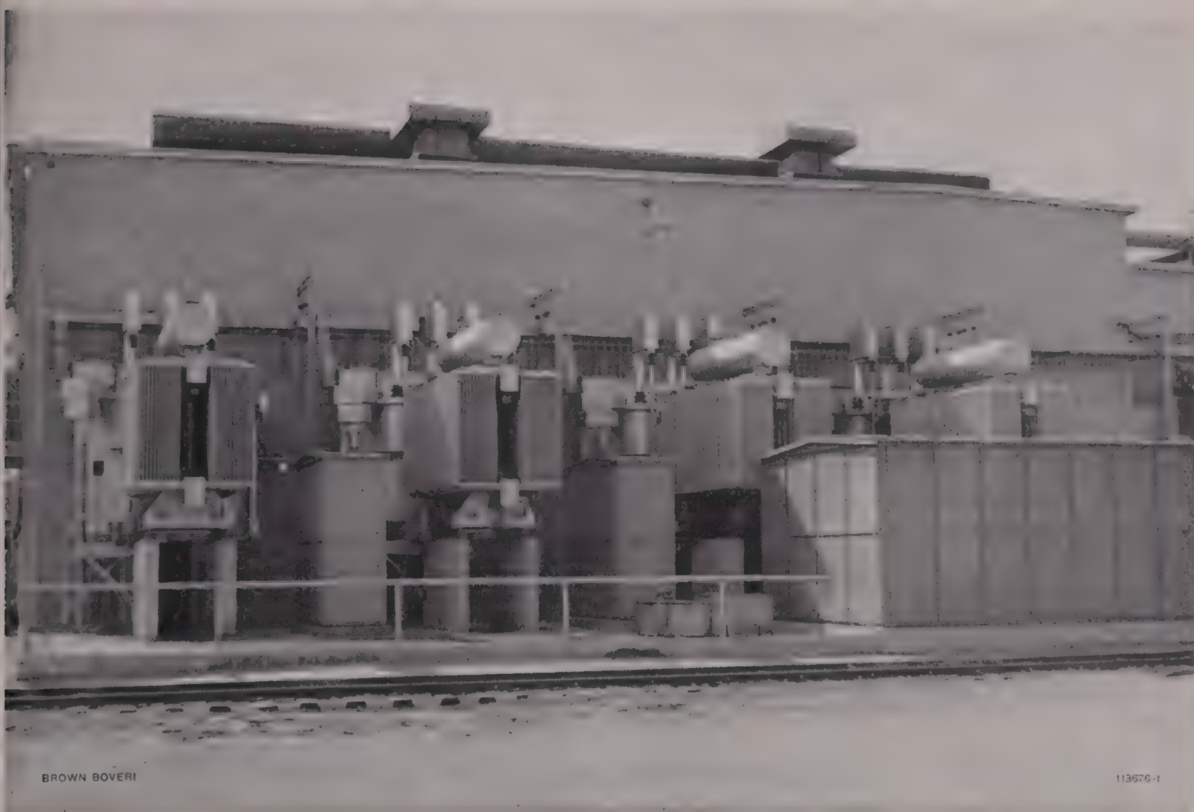


Fig. 20. – Rectifier transformer installation for 160 kA

Four transformer units are visible, four more are on the opposite side of the building.

sheet or, for windings with several turns, from pieces of copper of the appropriate shape. Generally these windings are only insulated with a thin coat of varnish and are easy to keep cool. When thin copper plates are used, the additional losses can be reduced to a minimum.

Great care has to be taken with the connecting bars carrying the current, i.e., by allowing for the magnetic fields produced, to choose an arrangement with which the additional losses and forces are as small as possible (Fig. 15). If heavy currents are carried by several parallel sets of bars, it is important to ensure that these have the same resistance and impedance and that a uniform distribution of the current is attained (Fig. 16).

In order to save space, the whole system of secondary connecting bars should be mounted in a single plane. Metallic constructional parts in the vicinity of unavoidable stray fields must be made of non-magnetic material, so as to avoid losses and heating by eddy currents. This particularly applies to the tank cover. However, it is sufficient to fit barriers of non-magnetic material between the individual heavy-current bushings, to prevent the magnetic flux from spreading.

By incorporating the control chokes in the tank of the main transformer, not only is the overall efficiency improved due to the reduction in length of the secondary bars, but considerable space is saved. Where possible the regulating and phase-shift transformers are also accommodated in the same tank (Fig. 8 and 17). Thus from the erection and circuit aspects there is only one unit between the primary network and the rectifier.

Since the Buchholz relay has proved indispensable for all kinds of transformers and since it is desirable to provide an oil conservator, Brown Boveri equip all their heavy-current transformers with this device (Fig. 18). The difficulties of oil leakage from heavy-current l.v. bushings has been overcome by employing a design which has already rendered excellent service.

Rectifier transformers of the above kind are almost always run continuously at full-load. In order not to have to reduce the output during an inspection, or if an isolated cooling element fails, the cooling capacity of water-cooled transformers is dimensioned so that it is assured even if the number of coolers is reduced. With air cooling, the closed oil circuit with natural cooling is adopted almost exclusively, to simplify the maintenance of the installation. For larger transformer units the naturally cooled radiators cannot be attached to the actual transformers; they are consequently combined to form a radiator battery which can be mounted remote from the transformer, if the latter is accommodated indoors (Fig. 19 and 20).

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THE SHORTING SWITCH FOR PROTECTING SILICON RECTIFIER INSTALLATIONS

621.382.2:546.28:621.316.9

Silicon rectifiers can only withstand short-circuit currents for a very short space of time, so that the conventional circuit-breakers cannot afford adequate protection for the rectifier, unless the latter is over-dimensioned, involving additional expense. Therefore, as has been proved on the mechanical or contact rectifier, it is advisable to short-circuit the diodes when a heavy overload occurs. The switch which does this is the shorting switch developed by Brown Boveri, and it short-circuits the transformer within 2·7 ms of the occurrence of the overload, and then trips the circuit-breaker protecting the transformer. The adjustable tripping of the shorting switch is effected at the very instant an overcurrent occurs, regardless of the momentary value of the current.

THE shorting switch was originally devised to protect the mechanical rectifier against backfires. Lately it has been utilized to protect silicon rectifiers because, owing to its extremely short operating time, it responds more rapidly to inadmissible currents and prevents them from affecting the diodes; its operation is more rapid than that of the a.c. and d.c. circuit-breakers, where not only the mechanical operating time has to be taken into account, but also the time taken to extinguish the arc. The shorting switch, though, is never alone in protecting the rectifier, but is always augmented by one or both the above circuit-breakers.

The design and principle of the shorting switch, which was originally devised to protect the mechanical rectifier, has been adequately described in other publications.[1] Its main disadvantage, from which shorting switches based on other principles also suffered, was that when the short-circuit current increased, the contact pressure tended to diminish owing to the electro-mechanical forces. Consequently it was limited to short-circuit currents having a peak value of 50 kA. With the aid of the tripping mechanism of the shorting switch, comprising a holding relay with auxiliary control contacts, it is possible to short-circuit the a.c. bars (between the transformer and the rectifier) and the d.c. busbars in less than 2·7 ms, thus protecting the contacts against harm by the arc. The auxiliary contacts actuate the a.c. and d.c. breakers which completely isolate the rectifier.

With increasing rectifier ratings, larger short-circuit currents had also to be taken into account. As a result of redesigning the shorting switch to eliminate the above weakness, the peak short-circuit current was raised to 200 kA.

[1] E. ROLF: Der Kontaktumformer, Springer Verlag, Berlin/Göttingen/Heidelberg 1957.

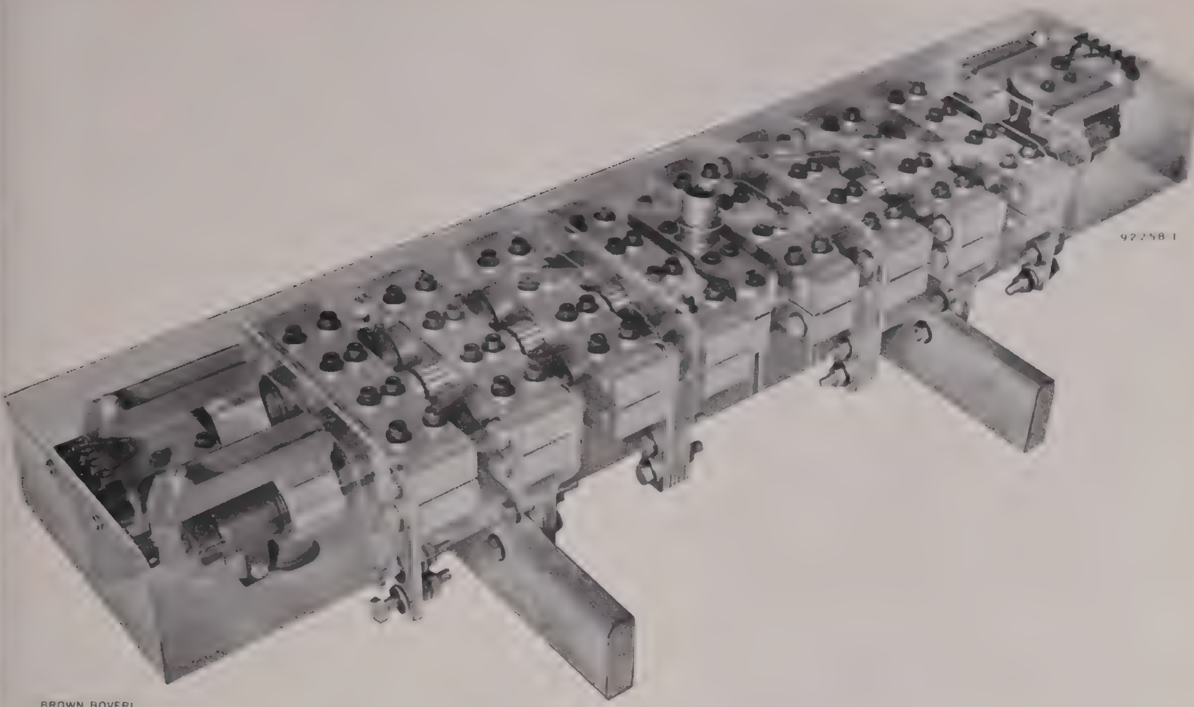


Fig. 1. – Shorting switch with transparent plastic hood

Clearly visible are the eight solid connecting clamps, guided and pressed together by a pair of strong bolts. The projecting eccentric socket-head spindle in the middle is used for resetting the closed switch by hand. At both ends are the tripping relays. The two lengths of wood below the switch are only required for transport.

The shorting switch illustrated in Fig. 1 has eight connecting clamps for the a.c. and d.c. busbars. In between are six contact points which create a metallic bond between the clamps when the switch closes. The actual contact system consists of the lightweight cylindrical contact pieces mounted on an insulated switchrod, which are forced into the fixed contact sleeves at the high ultimate speed of 3 m/s. The sleeves are split into a number of segments which press against the entire periphery of the moving

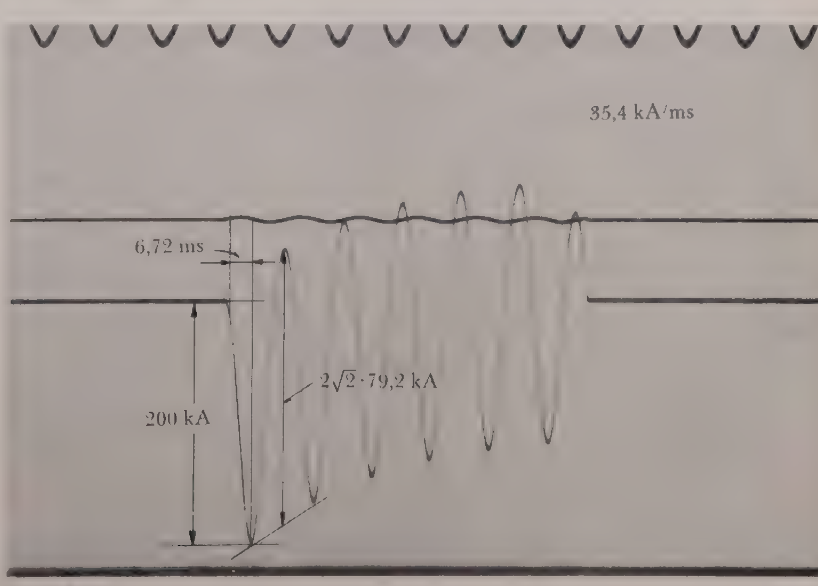


Fig. 2. – Dynamic test of a shorting switch at a peak short-circuit current of 200 kA during 6 cycles

Rate of rise of current 35·4 kA/ms

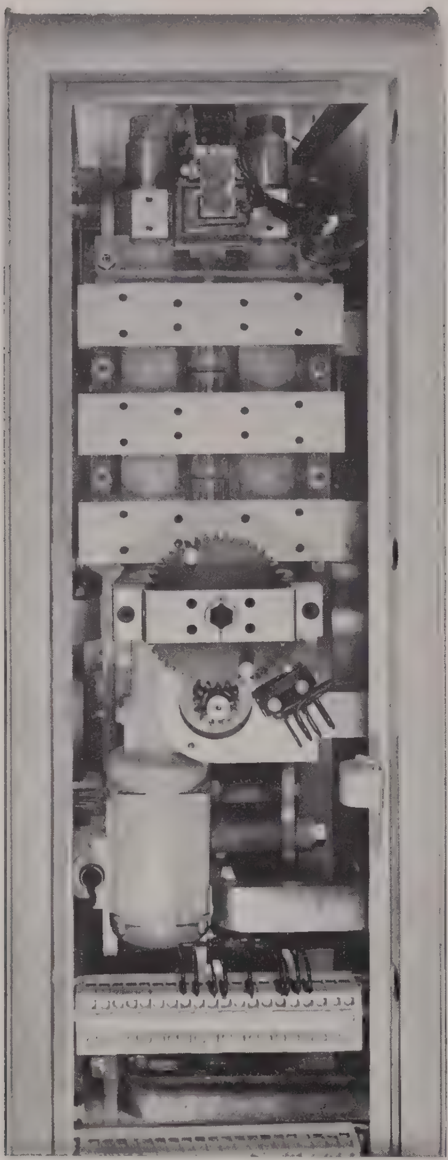


Fig. 3. – Triple-pole shorting switch with resetting motor, incorporated in a silicon rectifier cabinet

contact piece. By dividing the flow of current through several parallel paths in the same direction, the contact pressure was increased due to the electro-dynamic effect, thus increasing the short-circuit strength. The shapes of the two sets of contacts were so designed that despite the high energy of impact, which is, effective at the first instant the contacts touch one another when closed very rapidly, the contacts never chatter and therefore suffer very little erosion.

The shorting switch constructed on the above lines was subjected to comprehensive tests in the short-circuit laboratory. Practical experience with contact rectifiers installed under widely varying circumstances has been very satisfactory as regards the performance of the shorting switch. In recent years over 150 such switches have been manufactured and installed with marked success.

Fig. 2 shows the oscillographic record of a test to check the dynamic strength of the shorting switch with its contacts closed. The short-circuit current in this case amounted to 200 kA (first aperiodic peak value), which represents a r.m.s. short-circuit alternating current of 79·2 kA. This current was carried by the shorting switch for 6 cycles, the rate of rise being 35·4 kA/ms. This excellent result proves the ability of the switch to withstand short-circuit currents up to 200 kA.

The continued development in the rectifier field led to the construction of a triple-pole shorting switch with the same components as its predecessor (see Fig. 3). This switch has also been tried out in practice; as experience with 30 such switches has proved, it performs its duties just as well as the shorting switch of the larger type. Having obtained very good results on test, the switch was released for use with rectifiers installed in traction vehicles. To determine the effect of vibration it was tested on a bumping machine, being subjected to an endurance test of about 100000 bumps with acceleration in different directions at varying rates, without any noticeable difference being observed in the switching properties. When mounted undamped the switch still functions satisfactorily with an acceleration of 16 g (where $g = 9{\cdot}81$ m/s^2). When mounted on shock-absorbing elements higher rates of acceleration up to 27 g are admissible.

When the shorting switch has tripped, it is reset either by hand with a lever, or by a resetting motor operated by push-button. In the latter case the installation can be remote controlled, which is ideal for rectifiers installed in traction vehicles or railway substations.

Technical Data of the Shorting Switch

Ratings

Maximum peak value of the a.c. short-circuit current for a maximum of 120 ms	200 kA

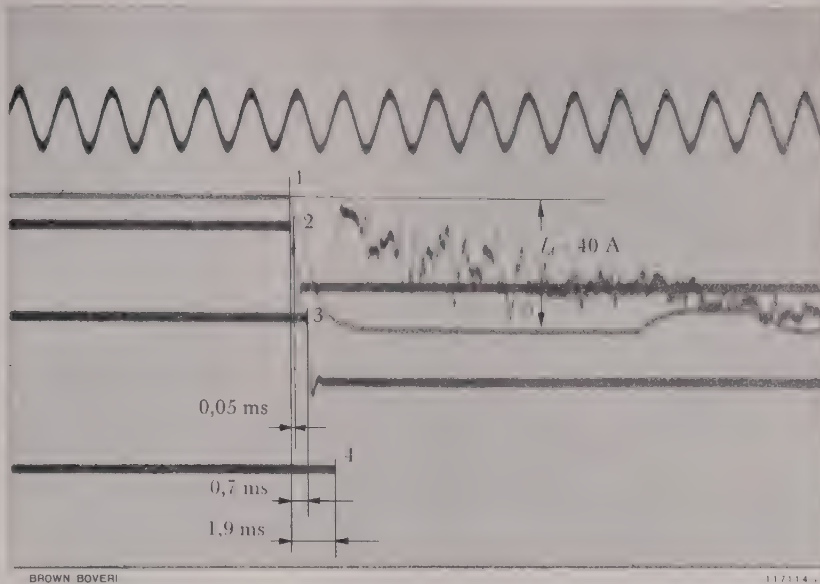


Fig. 4. – Measuring the timing of the operation of a shorting switch

I_A = Tripping current
1 = Current begins to rise
2 = Armature attracts
3 = Switchrod starts to move
4 = Shorting switch closed

Service voltage	1000 V
Test voltage	3000 V

Timing

Make time of the shorting switch	1·9–2·7 ms
This time is divided between the mechanical and electrical actions as follows:	
Energizing the relay coil	5 %
Attraction of armature and mechanical unlatching	45–55 %
Closing action of the contacts	50–40 %

Fig. 4 shows an oscillogram illustrating the sequence of the operation of the shorting switch, from which it is easy to see that by far the greater part of the time is taken up by mechanical actions. Before a shorting switch is delivered, apart from having its dimensional tolerances and electric strength checked, its operation is accurately timed. The spare main contacts and tripping relay are checked for correct operation on a dummy switch to ensure the full functional reliability of the switch at all times.

The fraction of the closing time of the switch which is occupied by the actual closure of the contacts is between 0·9 and 1·2 ms. Fig. 5 shows the distance-time diagram of the closing operation for a switch in the brand-new condition in curve *a*, and after 1000 operations in curve *b*. It will be observed that the contact closure time becomes shorter the longer the switch is in service, resulting from the reduction in the friction at the switchrod guides and the operating spring.

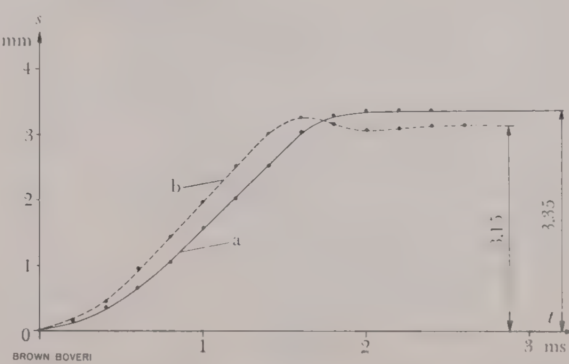


Fig. 5. – Distance-time diagram of the moving contact of the shorting switch during closure

a: In brand-new condition t = Time in ms
b: After 1000 operations s = Distance in mm

Electric strength of the triple-pole shorting switch for traction duty

Since the service voltages normally encountered in railway service are from 1500–2000 V, the shorting switch in Fig. 3 may be used for this purpose when its two contact points are connected in series, without any further modification. The test voltages of 5 to 7 kV are likewise fulfilled, so that the shorting switch also complies with the requirements of the standards in this respect.

(KME) E. KELLER

THE D.C. CIRCUIT-BREAKER TYPE ID

621.316.57.02

Although the principle of magnetic blow-out for stretching and extinguishing a d.c. arc has been used all over the world for many years, the present article will demonstrate that exhaustive studies and tests were necessary during the development of the new d.c. circuit-breaker, in order to attain the stipulated operational reliability and speed of action. The design of this new breaker is described, outlining the principle of arc extinction and the manner in which the auxiliary devices detect faults, concluding with the results of performance tests in the laboratory.

ONCE the fundamental mathematical and physical conditions governing the interruption of a direct current had been established, experimental development techniques led to the design of extremely reliable d.c. circuit-breakers. This all took place a number of years ago. The subsequent rapid expansion of large-scale electrolysis plants then necessitated the erection of installations with ever-increasing capacities. The silicon rectifier developed in recent years, with its high economic performance, underlines this trend. The result is that the possible fault currents caused by internal or external short circuits can rise to extremely high values within a few milliseconds. Since the thermal and mechanical stresses rise as the square of the current, efforts are directed towards providing quick-acting d.c. circuit-breakers to limit the short-circuit current in the shortest possible time, thus protecting the installation. Rectifier installations equipped with semiconductor diodes make one further stipulation, namely that switching overvoltages should be as low as possible.

Brown Boveri's long experience in the construction of high-power rectifier installations made possible the development of the batch-produced, high-grade d.c. circuit-breaker type ID (Fig. 1 and 2), whose main features are rapidity of action, reliability and ample reserve capacity. When installed with silicon rectifiers it can be augemented with a device which keeps the arc voltage down to a low limiting value.

Principle of Arc Extinction

The practical requirements which the d.c. breaker has to fulfil are that it must limit and interrupt any short-circuit current dependably and as rapidly as possible. Accordingly, as soon as a fault occurs, it disconnects the faulty line, extends the resultant arc in an arc-chute and holds it at constant length until it ceases to burn. During the whole of this period the arc voltage is certain to exceed the supply voltage.

It is well known that every length of the free arc corresponds to a definite arc characteristic. Assuming that the conditions of the freely burning arc can be transposed to a heavy-current arc burning in an arc chute, the following considerations are important. In the region of the contacts there is a corresponding point at which the arc characteristic intersects the straight line of the resistance characteristic (point A in Fig. 4). If the arc were not extended, it would continue to burn until the contact was destroyed. This phenomenon is known as the standing arc. However the arc is extended by means of the magnetic blow-out system, the arc voltage rising rapidly until the length of the arc has attained its ultimate value. Provided the arc characteristic does not deteriorate during the time it is burning, as a result of overheating, etc., and there is consequently no intersection with the characteristic of the supply system, the energy stored in the system inductance is dissipated and the arc extinguished. During the time the arc is burning, the source of voltage continues to give up energy; the longer the arc burns, the greater

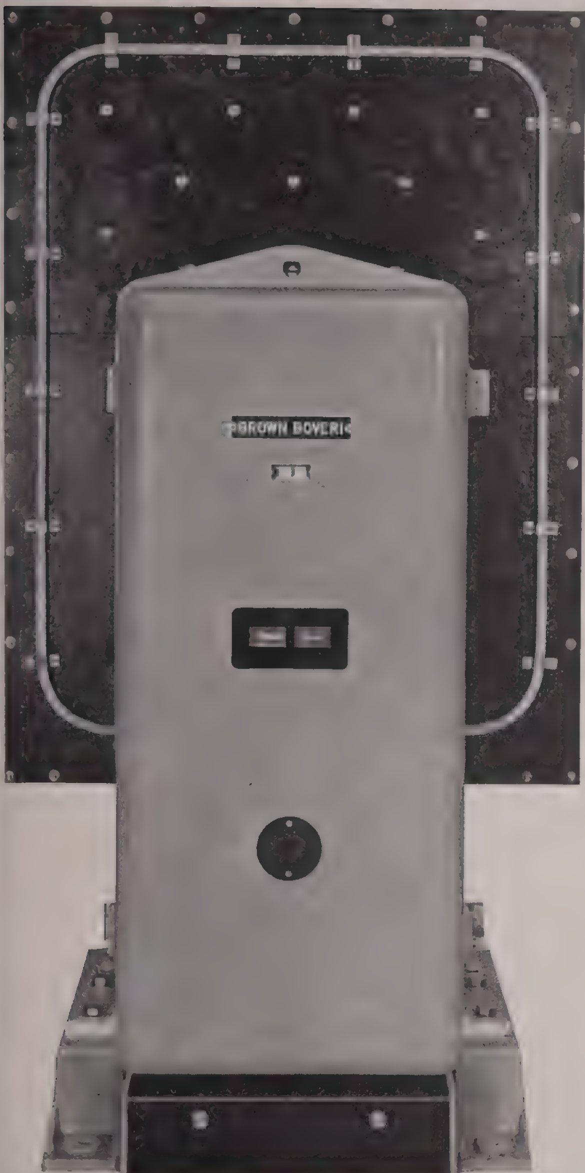


Fig. 1. – View of the d.c. circuit-breaker type ID from the front, showing the casing for the operating mechanism

Rated voltage	1500 V
Rated current	10 kA
Maximum breaking current	80 kA
Total operating time with di/dt-release, from attainment of the tripping limit to parting of the contacts	5·5 ms

Various combinable methods of tripping:

Static overcurrent relay adjustable 8–18 kA

Static reverse-current relay adjustable from 600 A

di/dt impulse release adjustable 1–4–10 kA/ms

Undervoltage release

Emergency manual release

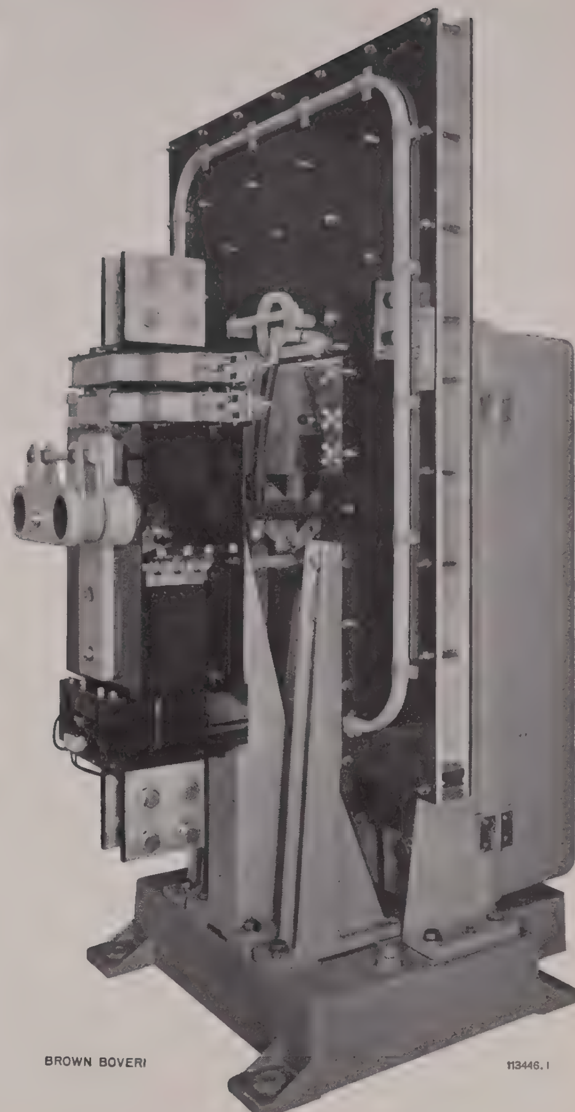


Fig. 2. – Side view of the d.c. circuit-breaker type ID

Fitted at the top end of the connecting bars are the overcurrent relay and reverse-current relay; at the bottom is the impulse current transformer. The detachable transparent plastic plate covering the arc chute permits the contact region to be inspected at any time and, after removal, allows the contacts to be replaced with ease.

the energy, or in other words, the larger the system inductance, the lower the arc overvoltage. Hence the entire interrupting operation is a question of energy. If the exact physical conditions governing the extinction of a heavy-current arc in an arc-chute were known and were maintained during stabilization, it would be possible to accurately calculate the variation of the current and voltage. But the conditions

are continually changing during the interruption and, under certain circumstances, may differ from one operation to another. Considering that the arc moves from the contact zone at the speed of sound, and its uniform extension and its limitation pose a very special problem influenced by all kinds of factors, it is not hard to realize that the small amount of knowledge of physical phenomena which we possess, and that which can be gained from basic experiments, can only be utilized to a relatively small extent for the design of a new arc-chute. If this knowledge is taken as a basis, it is nevertheless necessary to keep to the procedure adopted for previous development, with several prototypes, in which the switching test with its qualitative and quantitative results is particularly valuable.

Constructional Design

The task of developing a new circuit-breaker from scratch, according to a definite basic principle, permits the designer to combine general operational experience on the one hand with modern constructional techniques on the other. The new d.c. circuit-breaker type ID, designed on these lines, combines the attributes of reliability, versatility and easy maintenance. These properties were attained by means of a robust construction, by combining parts associated functionally into sub-assemblies, and by employing modern materials. The system of designing in sub-assemblies leads to a very clear layout. Each mechanically integral element is independently mounted and, if necessary, can be dismantled and overhauled separately. These elements are interconnected with one another, after assembly, by carefully selected, adjustable links, according to the functions they have to perform.

The breaker can be subdivided into the three main parts: the operating mechanism, the main contact assembly, and the arc-chute.

Operating Mechanism

All the parts belonging to the operating mechanism (Fig. 3) and the complete electric automatic-control system are enclosed in a dust-tight casing. On opening the casing cover, all parts are easily accessible. Mounted at the bottom is the reloading motor, which can be supplied for 380/220 V, three-phase a.c., or for 110 V d.c. The motor can be controlled at any of the normally stocked voltages, simply by replacing the plug-in contactors. The motor sub-assembly can be dismantled with only a few manipulations, operated alone and tested if necessary. The remaining sub-units, enclosed in the breaker casing, are: a supplementary airblast system, required for low currents up to about 80 A; a loading system for the cycles "load" and "close", a latching device for the breaker, a tripping device and, in certain cases, an electric supervisory sub-unit for the polarization circuit of the static reverse-current relay.

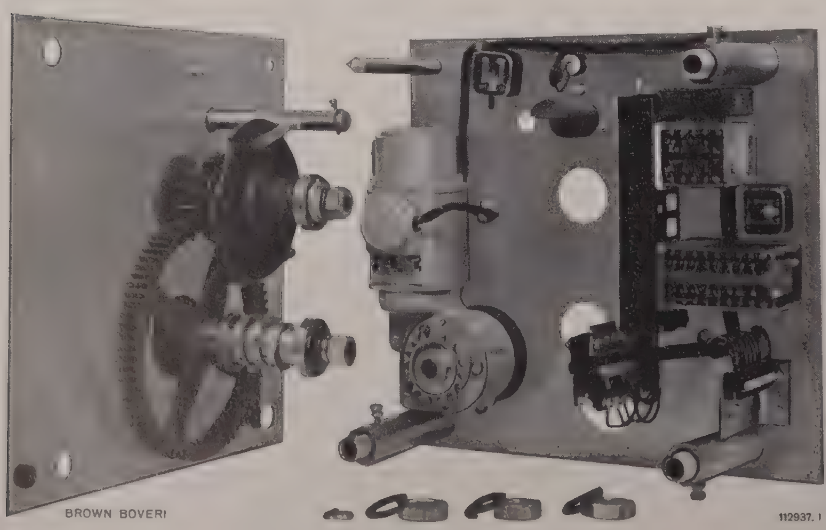


Fig. 3. – Motor-driven operating mechanism, removed from the breaker and opened

The electric automatic-control section and the mechanical section are mounted separately on the two back-plates.

Main Contact Assembly

This assembly carries the connecting bars and the main contacts. Also attached are the various measuring elements which detect the tripping criteria. For the steady-state measurements these elements are an overcurrent relay and a polarized reverse-current relay; for the di/dt release an impulse current transformer.

The manner in which the operating mechanism functions follows automatically from the choice of a latching device as the tripping element, this being directly unlatched by the built-on release. Consequently the working cycle, which is in three distinct parts, commences with loading the closing spring; this is performed automatically after every interruption. During the closing movement first the extinguishing contacts close, then the main contacts; any excess energy in the motion is dissipated by an oil-filled shock absorber. The tripping impulses of the overcurrent or reverse-current relay, and the undervoltage trip act directly on the release. The impulses of the current transformer are selected for direction, passed through adjusting elements and then applied to the appropriate coil of the release. The release itself is an extremely rapid blocking solenoid with an inherent operating time of 0·5 ms. Its falling armature, on reaching the pick-up limit, acts directly on the latch and initiates the action of opening the breaker. Special attention was devoted to the design of these elements. Despite the severe stresses, the latches exhibited hardly any traces of wear after 20000 operations in the laboratory; this was the result of choosing a suitable shape and high-grade materials. On interruption, the excess energy is effectively and uniformly dissipated at the end of the movement, by means of two controlled oil-filled shock absorbers.

Arc-Chute

In the d.c. circuit-breaker type ID the main and the extinguishing contacts are separate; the main contacts open first. Their contact pieces are designed to withstand the thermal and dynamic stresses imposed by all sustained currents up to 10 kA and breaking currents up to 80 kA. When these contacts have opened, the current commutes to the extinguishing contacts. For constructional reasons it is desirable for the clearance between the open extinguishing contacts to be as small as possible. Its minimum value is laid down by regulations on the one hand, while, on the other, if the clearance were too small and the arc path were insufficiently deionized in the region of the contacts, this could lead to restriking. But if the clearance is small, the mass of the moving contact piece can be lighter, thereby permitting greater acceleration during opening. Viewed from the electro-dynamic aspect, the forces tending to force the contacts apart are smaller when the contacts are small. They can be kept small when the shape of the contacts is carefully designed, and the leads well arranged (Fig. 4).

In the d.c. breaker type ID the moving contact is in the form of a roller, as this offers notable advantages with respect to erosion and replacement. Dynamically it can withstand all currents up to 80 kA; also by specially shaping the horns and connecting leads it is possible to achieve a strong inherent blow-out effect. This effect is augmented by two additional, inner blow-out coils. From the region of the contacts, immediately the latter part, the two partial arcs produced are rapidly united and forced into the arc-chute.

As soon as the arc leaves the vicinity of the contacts, it commutes on to a pair of run-out horns. In doing so the "outer" blow-out system is switched on. The turns of the coils are run along the horns in such a way that the arc footing on the horn is subjected to a strong magnetic field. The rest of the coil is of such a shape that, as soon as the arc footing has been driven rapidly to the end of the horns, the middle part of the arc is forced upwards and its ends confined to the extremities of the horns. This length produces the maximum arc voltage. In low-inductance networks it is seldom attained, because the arc has ceased to burn before it reaches this stage, i.e. the energy stored in the network has been dissipated. For highly inductive networks, above all those in which silicon rectifiers are employed, the arc voltage is limited by providing special short-circuiting loops and by splitting the arc into two, and imposing a form of potential control on the arc by special means. Consequently the partial arcs burn with a relatively constant length and run uniformly along the horns.

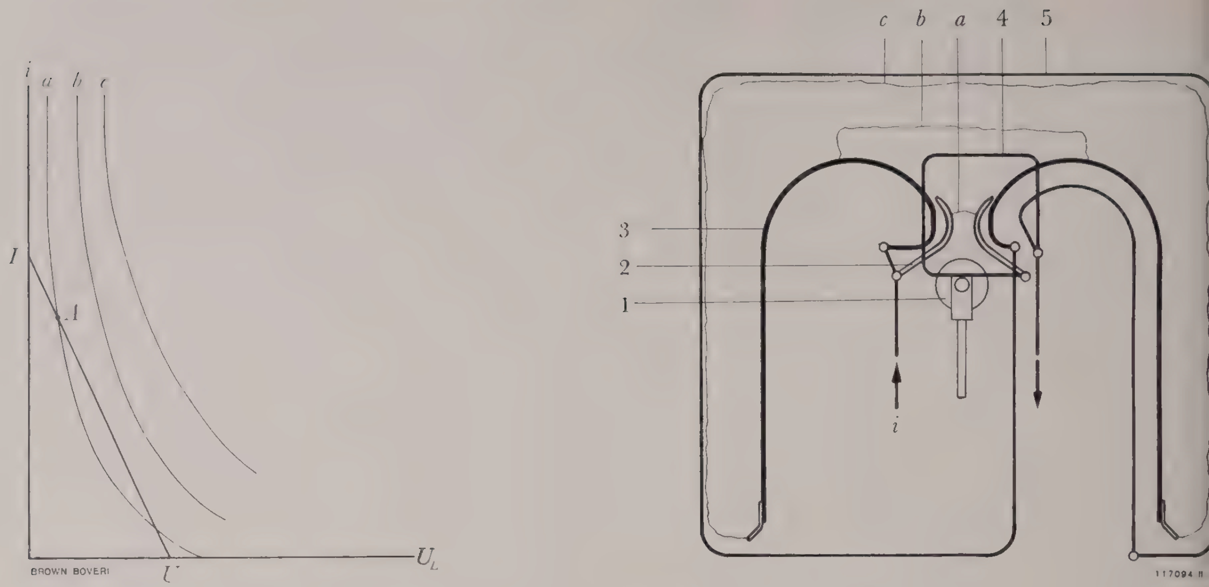


Fig. 4. – The principle of arc extinction employed in the d.c. circuit-breaker

Only half the number of symmetrically mounted blow-out coils are shown.

1 = Moving contact 2 = Fixed contact 3 = Run-out horns 4 = Inner blow-out 5 = Outer blow-out coil

In the course of its movement the arc *a* commutes on to the horns as arc *b*, thereby switching on the outer blow-out coil 5. In the final stage it stabilizes itself as arc *c* under the control of the outer coil.

Diagram on the left: Sequence of arc characteristics during interruption

U_L = Arc voltage
i = Arc current
U = Mains voltage
R = Resistance of d.c. circuit
$I = U/R$ = Steady-state current with breaker closed
$\overline{IU}$ = Resistance characteristic

In the region of the contacts (arc *a*) the associated arc characteristic *a* intersects the straight-line resistance characteristic (stable point *A*). But the arc must be stretched, as a result of which the characteristics *b* and *c* until the arc is extinguished are always above the resistance line.

At the end of the arcing time the special design (from thermal considerations) of the region surrounding the horns ensures that the arc voltage cannot drop so far that it reverts to the restriking voltage. As mentioned already, a supplementary air blast extinguishes low currents up to about 80 A, for which the effect of the magnetic blow-out would be inadequate.

Tripping Elements

The d.c. breaker type ID is tripped electrically by the holding armature of the release (Fig. 5) falling. The release has a power reserve of three to five times the necessary power, in order to keep its mechanical operating time as short as possible; sticking is therefore prevented. The release can be employed as an undervoltage trip without hesitation. The energizing current of the release is set to a fixed value, at which a definite steady-state current in the impulse winding causes it to trip. As a result the impulse current transformer can be tested on its own. Only the mechanical emergency release acts directly on the tripping lever of the latching device; if required, it can also be operated from outside the breaker cell.

The static trip by the overcurrent relay or by the polarized reverse-current relay is also effected by interruption of the energizing winding of the release (Fig. 5, 5). Compared with the d*i*/d*t* release to be described later, the switching time-lag is about 1·5 ms longer. Owing to the relatively slow rate of rise of the overcurrent in service, this does not prove troublesome. In the event of a short circuit in the forwards or reverse direction, an impulse current transformer fitted on the breaker acts through direc-

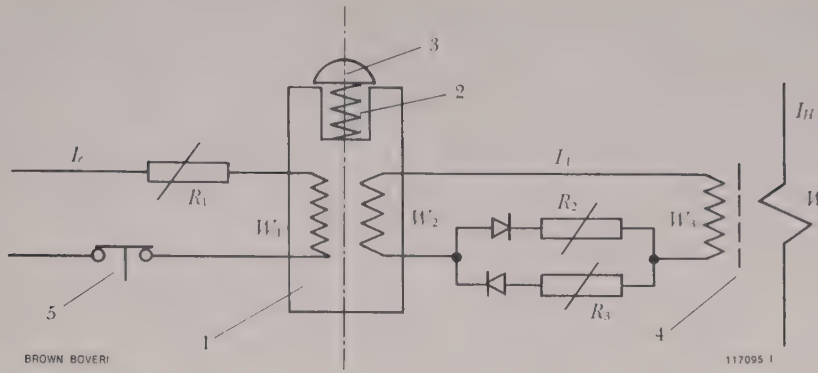


Fig. 5. – Circuit diagram to show the principle of impulse tripping

1 = Release
2 = Spring
3 = Armature
4 = Impulse current transformer
5 = Interrupting contact

I_e = Energizing current
I_A = Tripping impulse current
I_H = Main current
R_1 = Resistor for setting energizing current
R_2/R_3 = Resistors for setting forward and reverse impulse currents

W_1 = Energizing winding
W_2 = Impulse winding
W_3 = Secondary winding of impulse current transformer
W_4 = Primary winding of impulse current transformer

tional elements on the impulse winding of the release. Up to very heavy currents this transformer has a linear characteristic so that forward short-circuit currents, for instance, immediately following a normal operational overload up to the limit of the pick-up value of the static overcurrent relay, are detected fully and cause the breaker to be tripped with the corresponding rapidity.

When equipped with the above tripping devices the d.c. breaker is able to fulfil all the conditions stipulated. In the majority of cases the type ID breaker is employed for protective duties. An appropriate supervisory device attends to the control of the breaker. In addition to preventing "hunting" following closure on a short circuit or overload, it assures that all the various tripping elements are ready for operation again immediately the breaker has tripped.

Supervision of the polarization circuit of the static reverse-current relay prevents the breaker from closing when the circuit is interrupted. On the other hand, when the breaker trips, the polarization circuit is automatically interrupted for a brief moment to prevent the armature of the relay from sticking.

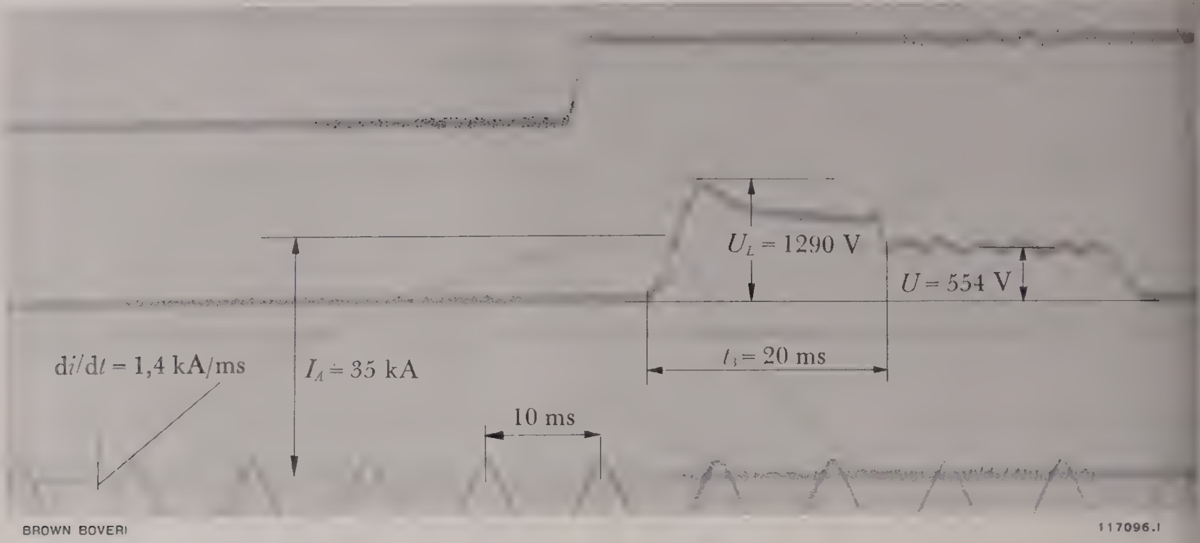
Test Results

Apart from checking the electrical switching capacity, the test on the type ID d.c. breaker has to include extremely accurate measurement of the mechanical properties. Since the various sub-assemblies are separately detachable they can be tested individually before incorporation in the breaker. The outcome of this method is that the final test on the breaker can be considerably simplified as all the components of the breaker are known to be sound. Owing to the extremely rapid movements, lasting only a fraction of a millisecond in some cases, electronic measuring equipment and a slow-motion camera had to be employed during the development of the breaker.

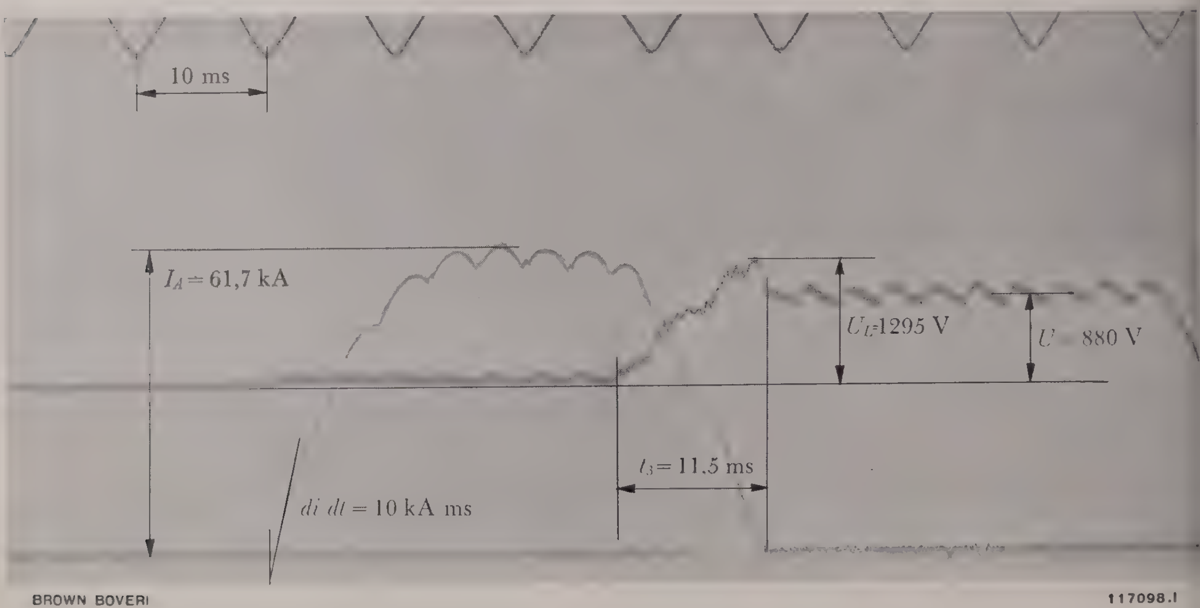
In spite of the very large forces employed to release the breaker, only a very small force (a few kilogrammes) is actually required. For tripping by the impulse coil of the release a power of about 2·5 W is sufficient.

The IEC recommendations regarding the temperature rise of the breaker were taken into account in the design of the type ID breaker. Following heat runs, during which the temperature was supervised by means of recording instruments, it was evident that the various current-carrying parts of the main circuit were amply dimensioned.

Since the breaker is designed for a maximum rated voltage of 1500 V d.c. and a maximum arc voltage of 2 to 2·5 times this figure may be produced on interruption, it was necessary to include stabilization of the arc in order to maintain the same conditions at



a



b

lower rated voltages. This is effected by reducing the volume of the arc-chute and by making the short arc travel a longer distance inside the chute. The arc-chute consists of a resistant material capable of withstanding large numbers of short circuits without being over-strained.

Due to the absence of any remanence in the region of the contacts, the breaker, after interrupting a heavy current in one direction, is perfectly capable of breaking any small current in the opposite direction.

In order to fulfil the different requirements with regard to the service voltage and the maximum switching overvoltage, the electromagnetic blow-out system also has to conform to certain stipulations. As a general rule it may be assumed that, for low service voltages, e.g. 220–550 V d.c., the supplementary blow-out effect in the middle part of the chute may be kept quite small, whereas at voltages of 1000 V or more, the magnetic blow-out should be fully effective in this region. Depending on the service voltage, and according to the requirements with

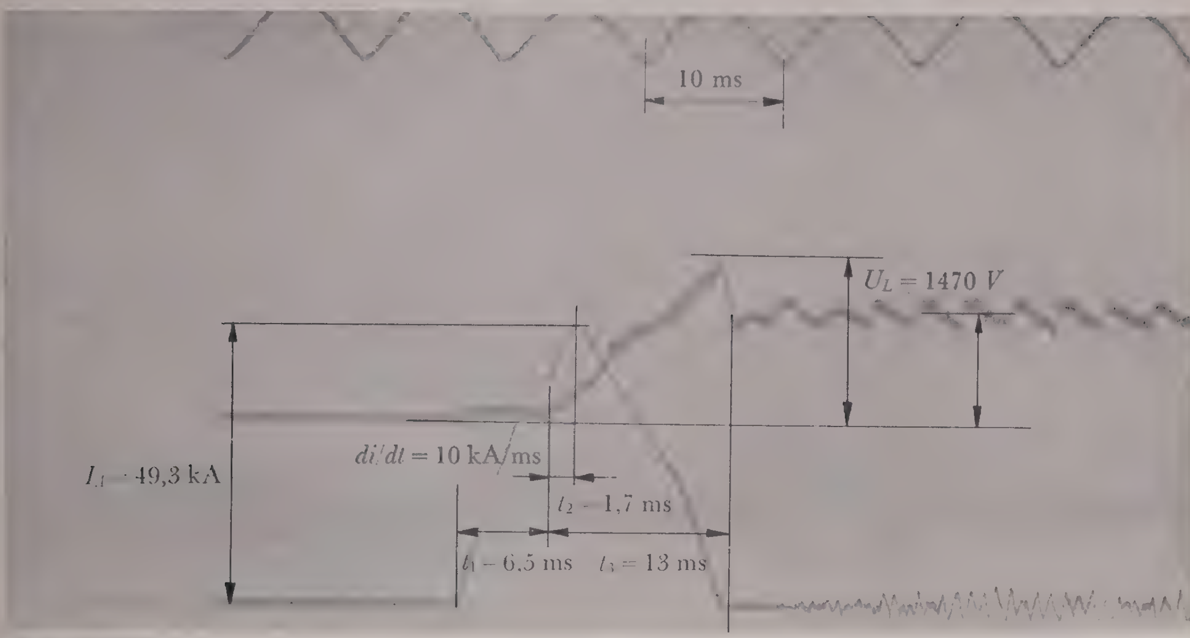


Fig. 6. – Oscillograms showing interruption by the d.c. circuit-breaker type ID under different operating conditions

U = Service voltage
I_A = Breaking current
$\mathrm{d}i/\mathrm{d}t$ = Rate of rise of current
U_L = Maximum arc voltage
t_1 = Operating time-lag
t_2 = Time till current begins to decrease
t_3 = Arc time

a: Stabilized interruption of an inductive d.c. circuit with current rise of 1·4 kA/ms, a peak current of 35 kA and maximum arc voltage of 1290 V at a restriking voltage of 554 V.

b: Interruption of a d.c. circuit with a current rise of 10 kA/ms, a peak current of 61·7 kA and maximum arc voltage of 1295 V at a restriking voltage of 880 V.

c: Interruption of a d.c. circuit (as in b) but with tripping by an impulse current transformer, thereby limiting the current to 49·3 kA. The maximum arc voltage amounts to 1470 V at a restriking voltage of 880 V.

regard to limitation of the arc voltage, the arc-chute may be equipped with supplementary elements.

The power test on the breaker covered very small to very heavy currents at d.c. voltages between 250 and 1760 V, with different inductances. At 880 V and rate of rise of current of 10 kA/ms, currents of up to 75 kA were interrupted. Above that by prematurely interrupting a 25-c/s half-wave before its natural zero, it was possible to interrupt currents up to a peak value of 86 kA at an r.m.s. value of the restriking voltage of 1000 V, and 115 kA at 250 V.

The oscillograms in Fig. 6 illustrate breaking operations performed by the d.c. breaker type ID under different operating circumstances. Fig. 6a shows deliberate tripping at relatively high inductance and low service voltage, with limitation of the arc voltage. Fig. 6b depicts a case where the current rose at a high rate to a high value, with deliberate tripping at an arbitrary moment. Fig. 6c shows interruption under the same conditions as in b but employing the di/dt release.

In spite of the different requirements which d.c. breakers have to fulfil nowadays, they are all within the range of capabilities of the type ID breaker, when a breaker for a rated current up to 10 kA is required. In existing installations, for example, where a silicon rectifier is installed for operation in parallel with d.c. generators, mercury-arc rectifiers or mechanical rectifiers, the need for a more rapid breaker with higher capacity may be expressed, to protect all the producers of direct current; the type ID breaker is ideal for this task. Its principal spheres of application are large electrolysis plants in the chemical industry, aluminium electrolysis plants, rolling mills and stationary installations feeding railway traction systems.

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(KME)

THE DESIGN OF SILICON RECTIFIER INSTALLATIONS

621.314.632:546.28

As regards the planning of complete installations silicon rectifiers offer certain advantages, which will be enumerated in this article. The design of a rectifier installation of this kind is described for a typical example, a project for an aluminium electrolysis plant.

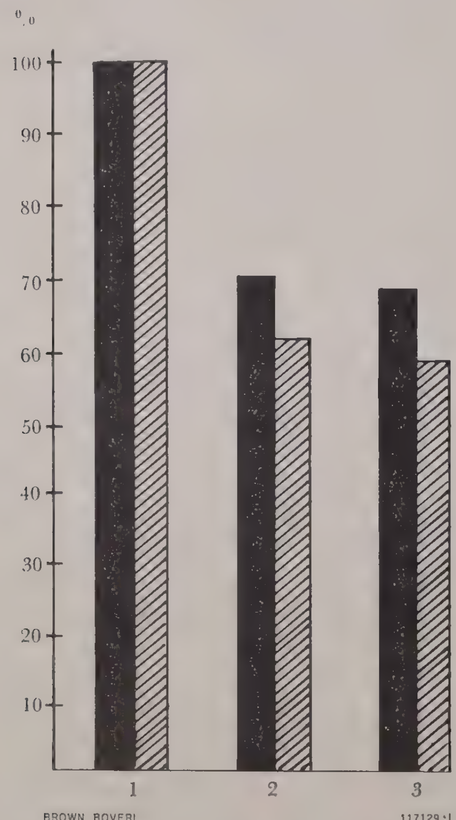

Fig. 1. – Comparing the space and floor area occupied by different kinds of rectifier installations

1 = Mercury-vapour rectifiers
2 = Mechanical rectifiers
3 = Silicon rectifiers

Space — Floor area

for the entire installation, i.e. including transformers, rectifiers, a.c. and d.c. switchgear, and auxiliary rooms.

FOR THE PLANNING and erection of complete installations the silicon rectifiers brought some noteworthy simplifications. Their practical introduction is therefore a marked advance in this respect, as is clearly seen from a comparison of the space and floor area occupied by different rectifier installations. If this comparison is extended to include every part of the installation, i.e. the transformers, the a.c. switchgear and any subsidiary rooms which may be provided, the result is definitely in favour of the silicon rectifier (Fig. 1).

The relatively light weight of the individual rectifier cabinets simplify transport and erection; there is hardly any need for special lifting and carrying equipment. Since the units do not contain any moving parts whatsoever, there is no need for special foundations; as far as the building work is concerned there is little more to the installation of a silicon rectifier than making the necessary connections, as for a switchgear panel. All live parts are safely enclosed inside the cabinet, so that no further precautions have to be taken in this respect. Extremely low temperatures, down to -60 °C, do not affect the operation of the silicon rectifier. The outlay for control gear is considerably less, compared for example with that required by the mechanical rectifier. One of the outstanding features of the silicon rectifier is the small amount of attention it requires.

A point which has to be carefully observed during the planning is how the power losses of the rectifier unit—which may amount to 10–15 kW, depending on the type—can be dissipated most conveniently. As was described in the article beginning on page 211, it was decided that air cooling would be best for the diodes. Fundamentally there are only two possible methods of removing the heat from the cabinet, namely:

open-circuit ventilation and
closed air circuit with transfer of the heat to water in a heat exchanger.

An open-circuit ventilation system is permissible when the air does not contain aggressive vapours or an undue amount of dust. The fresh air can then either be drawn in from outdoors and the warm air, at a temperature about 15 °C higher, blown out into the building, i.e. utilized for heating the rooms, or the air can flow in the opposite direction. If such favourable conditions do not obtain, or the air intake temperature is above about 40 °C, it is necessary to resort to closed-circuit cooling. Standardized designs are available, in which the heat exchanger is accommodated in the plinth of the rectifier cabinet. The total amount of air required is governed by the number of diodes to be cooled and, as stated on page 213, works out to about 1 m^3/s at inlet and outlet temperatures of 40 and 55 °C, respectively. From this it is easy to determine the necessary cross-section of the air ducting for the fresh and exhaust air, by substituting an air speed of 4 to 6 m/s.

On account of the large number of possible variants and the numerous special conditions which have to be observed by individual installations, it is hardly feasible to make any generally valid statement regarding the layout of the electric switchgear, including the control and protective gear, or regarding the arrangement of the rectifier cabinets. It must remain the task of the project engineer to study the specific requirements and, from the various possible alternatives described in preceding articles, to combine those which produce the optimum overall solution from the technical and economical aspects.

A typical example is depicted by Fig. 2 and 3, which show the layout of a silicon rectifier installation in an aluminium electrolysis plant. Six identical sets, each consisting of a transformer and six rectifier cabinets in three-phase bridge connection, provide the stipulated maximum service current of 108 kA at a voltage of 900 V (Fig. 2). Owing to the height of the voltage, each limb of the bridge utilizes a pair of diodes in series. The system ripple of each set is twelve-pulse; to improve matters in this respect, one group of three sets is displaced in phase relative to the other in such a way that the resultant ripple is twenty-four-pulse.

All the rectifier and regulating transformers stand in line along the outer wall of the building in the open air and are water-cooled (Fig. 3). This arrangement is almost compulsory from price considerations. The tank of the rectifier transformer also contains the phase-shifting auto-transformer with its tap changer

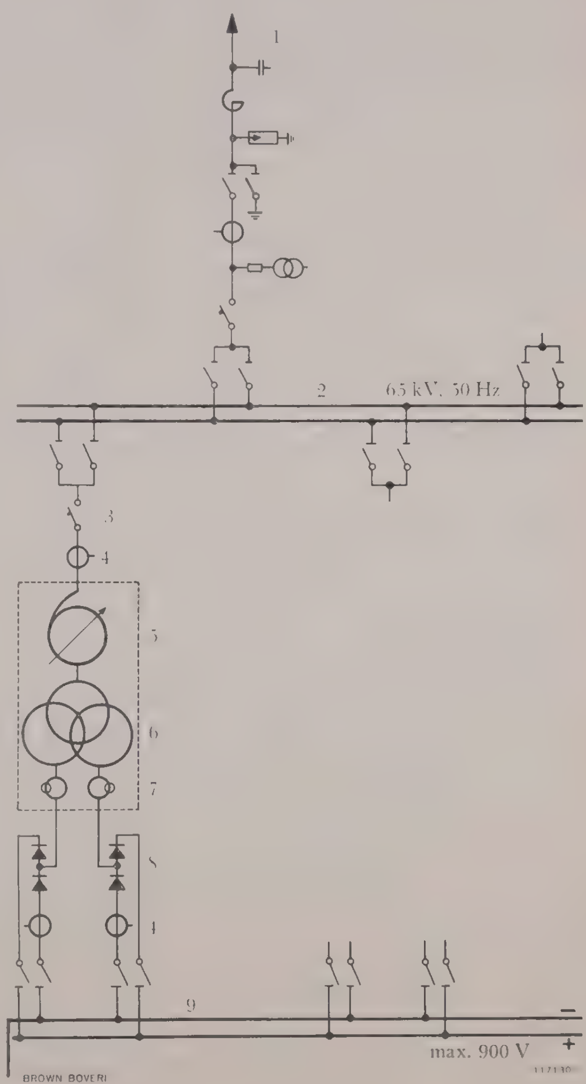

Fig. 2. – Circuit diagram of a silicon rectifier installation producing a maximum of 108 kA at 900 V

1 = 65-kV overhead line
2 = 65-kV duplicate busbar system
3 = Transformer circuit-breaker
4 = Current transformer
5 = Phase-shift regulating auto-transformer
6 = Rectifier transformer
7 = Control reactors
8 = Silicon rectifier cabinet
9 = D.C. busbars

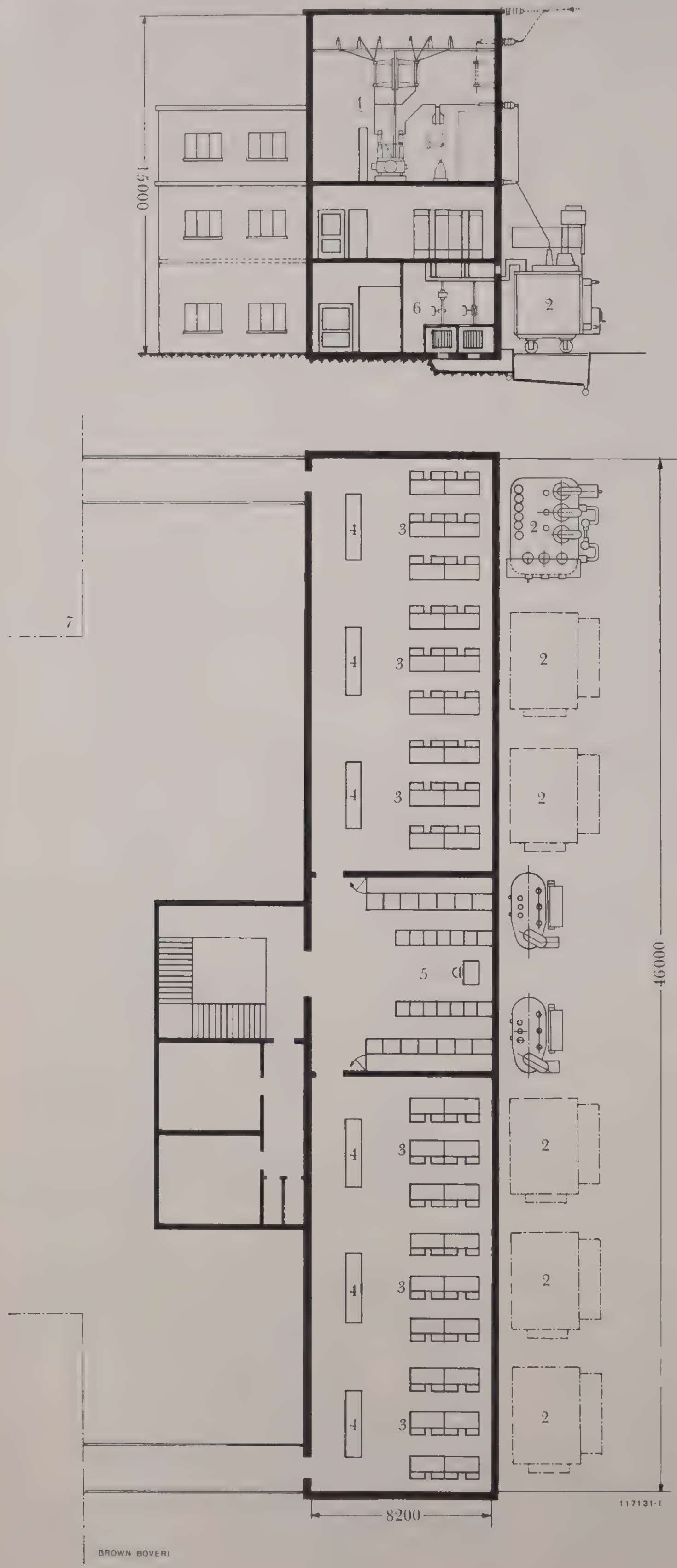

Fig. 3. – Layout of a silicon rectifier installation for an aluminium electrolysis plant

consisting of six identical sets, each with an outdoor transformer and six rectifier cabinets, producing a total output of 108 kA at 900 V. All the electrical equipment is housed in a three-storey building. The floor containing the rectifiers and the small control room is at the same level as the electrolysis shops, and is thus easily accessible from there.

1 = 65-kV switchgear
2 = Variable-voltage rectifier transformers
3 = Rectifier cabinets
4 = Rectifier switchboards
5 = Control room
6 = D.C. busbars
7 = Electrolysis shops

for voltage variation and the control reactors, which affords the following advantages. Space is saved, the whole unit can be assembled and tested in the factory, losses are reduced owing to the elimination of external connections; also the auto-transformer is well protected against short circuits (see page 227).

The position of the rectifier cabinets inside the three-storey building can be seen in Fig. 3. The incoming power from the 65-kV overhead line is first conveyed to the h.v. switchgear on the top floor (1) and from there to the outdoor transformers (2). On the middle floor, at the same height as the electrolysis shops, are the systematically arranged rectifier cabinets (3) and their switchboards (4). Situated in the middle of this floor in a single combined control room (5) are the switchboards from which the entire plant can be controlled and supervised. The ground floor contains mainly the d.c. busbars and auxiliary equipment. With this layout the stipulation of short connections between the transformers, rectifiers and busbars has largely been fulfilled. Additional losses in the cabling system, which in such heavy-current plants are an economic factor of considerable importance, are very small indeed.

In this case the system of cooling employing a closed air circuit and heat exchangers was adopted for the rectifier cabinets. Although the contamination of the air by the electrolysis baths was regarded as quite small, this solution was chosen as the price difference compared with the open-circuit version was insignificant. Thus dust is completely excluded from the rectifier cabinets and, at the same time, ventilation noise is prevented from becoming a nuisance.

Protection on the d.c. side is afforded by shorting switches fitted in the rectifier cabinets, which respond immediately to short circuits on the d.c. busbars, shorting the secondary side of the rectifier transformer on all three phases and thus causing the primary circuit-breaker to trip.

Should any of the diodes in the rectifier cabinets lose its blocking capacity, this is signalled in the electrolysis shop. The control room can see in which of the six sets the fault has occurred, while on the actual cabinet a signal lamp indicates the tier in which the defective diode is located (see also page 210). It is impossible for a reverse current to occur since, with the selected circuit arrangement, there are still three healthy diodes in series. The rectifier continues to run uninterrupted; neither the cabinet concerned nor the set needs to be disconnected. The defective diode can be replaced at the next convenient opportunity.

Whether and to what extent the control gear, and the protective and alarm devices should be concentrated in a single control room is a point which only the local works management can decide. In the example described, the entire electrical installation, on both the a.c. and d.c. sides, can be controlled from the central control room. Normally this is unmanned and only employed for switching operations, or when a fault is signalled; the regulation of the current and interruption in the event of a fault are effected automatically. The equipment of the control boards is therefore quite simple and includes merely the remote-control gear for setting the desired value of the direct current, ammeters, switches controlling the tap changers of the transformers, and their position indicators and fault indicators. The rectifier switchboards (4) contain all controls necessary for the a.c. and d.c. sides of each set, as well as the normal equipment for metering and signalling.

(KME) H. RUCKSTUHL

TESTING SILICON DIODES AND OPERATING EXPERIENCE WITH SEMICONDUCTOR RECTIFIER INSTALLATIONS

621.382.2:546.28

This article describes the methods used for testing Brown Boveri silicon diodes. It will be seen that, before leaving the works, every diode has to pass a severe and comprehensive test; the silicon diodes rated 600 V and 200 A are subjected to inverse voltages of 1200 V or more, and overload peaks up to 3000 A. Periodical measurements carried out on installations in service prove that, even after nearly two years continuous operation, the diodes employed show no signs of ageing. An interesting means of improving the overall efficiency, by changing over from existing mercury-arc rectifiers to silicon rectifier units, is illustrated by an installation already carried out.

SEMICONDUCTOR techniques have witnessed tremendous progress in recent years, since efficient germanium and silicon diodes were developed. Brown Boveri, bound by tradition to the rectifier field, have thoroughly studied these new techniques and have undertaken the development and manufacture of power diodes of their own design. In the course of this work germanium diodes were first developed for an output of 100 A with a peak inverse voltage of 120 V, three installations being equipped with them, producing a total output of 7000 kW. In spite of the excellent results obtained with these installations, the development of still more efficient units proceeded and silicon diodes for 200 A and a normal inverse voltage of 600 A were produced. Production of these diodes began on a large scale about the middle of 1960. In the meantime three installations with a total capacity of over 18000 kW have been equipped with Brown Boveri silicon diodes and taken into service.

Brown Boveri are well aware of the fact that, for many clients, equipment offered by a manufacturer must be able to show proof of trouble-free service over a long period before the decision is taken with regard to placing a large order. In addition it is just as important to be convinced that, before leaving the factory every diode, no matter how carefully it may be manufactured, is subjected to a strict, exhaustive test. The remarks which follow will therefore deal briefly with the methods of testing employed by Brown Boveri and will also provide some details of the experience gained with installations so far in service.

Testing Diodes in the Factory

The kernel of every semiconductor rectifier unit i[s] the semiconductor diode; consequently great impor[tance] is attached to manufacture and testing. Brow[n] Boveri have therefore devised their own methods o[f] testing, which take into account the physical pro[perties] of the semiconductors, simultaneously em[ploying] most up-to-date electronic equipment.

Testing During Manufacture of the Diodes

Already during manufacture extensive preliminar[y] tests are performed at various stages of completion[.] Particular importance is attached to measuremen[t] of the inverse characteristic of the diode when carry[ing] no load current. This measurement is performe[d] after each manufacturing operation, so that fault[y] elements can be eliminated at quite an early stage[.] Before the body is sealed, the variation of the blockin[g] current with load and the inverse characteristic ar[e] determined, the latter with the aid of a speciall[y] calibrated cathode-ray oscilloscope. Fig. 1 shows [a] test unit containing all the apparatus needed fo[r] performing these tests.

When manufacture is complete, each diode is sub[jected] to an exhaustive final test, the programme fo[r] which contains the following stages:

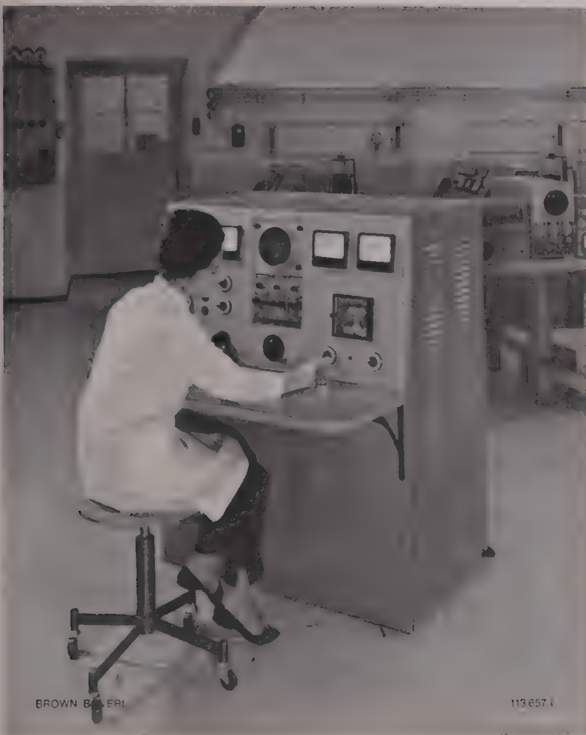

Fig. 1. – Unit for testing silicon diodes

The diode being tested can be seen behind the glass window on the right.

Fig. 2. – Brown Boveri silicon diode

The letter in the head of the cathode terminal pin denotes the classification of the diode with regard to its forward voltage drop. The rating and the serial number of the diode are visible on the hexagonal base above the screw threads.

Batch checks

In addition to checking the external dimensions, the truth of the threads and cathode terminal pin, and the glass seal, the following electrical measurements are performed with each diode.

a. *Measurement of the forward characteristic* at a mean direct current of 200 A, corresponding to a peak value of 600 A. According to the readings obtained, the diodes are classified as regards their forward voltage drop, for the eventuality of their being connected in parallel later.[1] This classification is effected according to the point of view that, when diodes of the same category are directly paralleled, a maximum deviation by the current of ± 15% of the mean value is assured. The category of each diode is marked in the head of each cathode pin (Fig. 2). Only diodes with the same marking are then employed in an installation.

b. *Measurement of the inverse characteristic* with the diode unloaded, at rated load of 200 A, and at 50% overload, i.e. 300 A, with inverse voltages having a peak value of over 1200 V. All these measurements are performed when a temperature of 110 °C prevails in the test orifice in the anode screw fixture.

c. *Impulse test.* Next follows the impulse test on the diodes, in the course of which they are subjected to 15 current half-waves with a peak value of 3000 A, and lasting 10 ms. The dead time between impulses is likewise 10 ms. These impulse trains are repeated five times at intervals of 1 s. In the pause between impulses the inverse current is measured at a PIV of 1200 V, using an oscilloscope. The variation of the inverse current during this impulse test is an indication of the stability of the diode. This test can detect diodes with

[1] See pages 176–192, especially chapter 3.

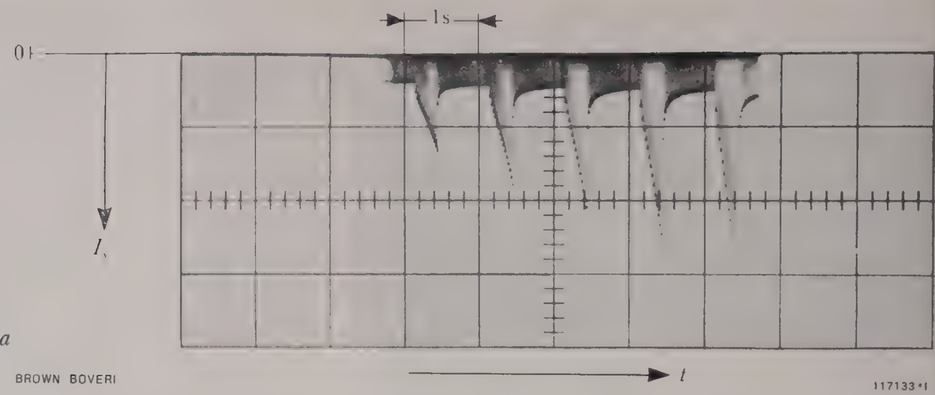

Fig. 3. – Impulse test on a silicon diode

The oscillogram shows the growth of the inverse current during the course of the test, in which the diode is subjected to 15 current half-waves with a peak value of 3000 A, repeated five times at intervals of 1 s. Between each current impulse the inverse current is measured at a peak inverse voltage of 1200 V.

t = Time I_s = Inverse current

extremely small internal defects and irregularities, and these diodes can be discarded. Fig. 3 shows the oscillogram of the inverse current during a test of this kind. The scale of the time axis is 1 s to each square. It will be observed that the inverse current increases during the succession of 15 impulses, owing to the temperature rise in the semiconductor layer. During the following 35 periods in which no impulses are applied, the inverse current drops very rapidly and has almost regained its initial value by the time the next succession of 15 impulses begins. This oscillogram shows that, after the fifth impulse train, the inverse current is roughly eight times as high as it was at no-load, whereas at rated load it attains only twice the initial value, as shown in Fig. 4.

d. *Re-check.* Following the impulse test, the forward and inverse characteristics are again measured, as described in a and b, and recorded photographically. If a diode is sound there should be no difference between the characteristics recorded before and after the impulse test. Diodes which do exhibit differences are rejected.

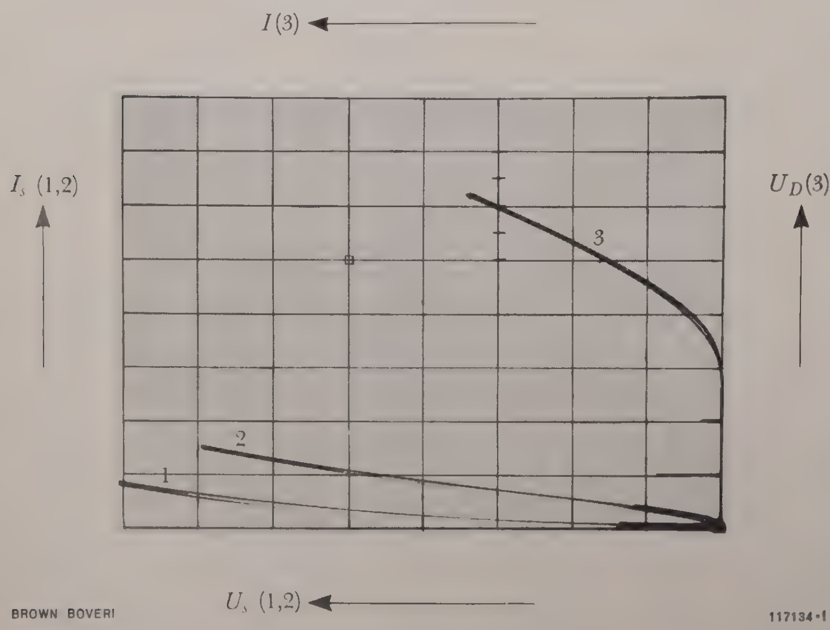

Fig. 4. – Test characteristic of a silicon diode

The inverse and forward characteristics of every diode are recorded photographically

1 = Inverse characteristic at no-load
2 = Inverse characteristic at rated current 200 A
3 = Forward characteristic
I_s = Inverse current (curves 1 and 2)
U_s = Inverse voltage (curves 1 and 2)
I = Forward current (curve 3)
U_D = Forward voltage drop (curve 3)

These measurements are all performed by methods devised by the Company, using the most modern equipment available. For every diode a test card is prepared, complete with a photographic characteristic, an example being shown in Fig. 4. The curve 1 shows the inverse characteristic of the unloaded diode at a temperature of about 20 °C and with a PIV of over 1200 V. The curve 2 shows the inverse characteristic of the diode when carrying its rated load of 200 A (mean value) with a PIV of roughly 1200 V, the temperature of the diode in this case being 110 °C. The third curve shows the forward characteristic. For this oscillogram the current and voltage deflections are interchanged, i.e. the axes are turned through 90 ° relative to the other oscillograms. The current scale for I is 200 A per division and the voltage scale for U_D is 0·2 V per division. It will be observed that the forward voltage drop of this diode amounts to exactly 1·2 V at the peak current of 600 A. On the left of the oscillogram the serial number of the diode is also photographed, thereby ruling out the possibility of a card being attached to the wrong diode.

Type tests

In addition to the ordinary batch tests, load tests are periodically carried out under exaggerated conditions. For these tests six diodes are selected from current production at random and subjected to an endurance test lasting 15 hours at overloads of 25 % with respect to both voltage and current. These tests are performed in a three-phase bridge circuit connected to a power transformer with a r.m.s. voltage of 535 V, which corresponds to a PIV of 760 V and an output d.c. voltage of 720 V. The direct current per diode in this case is 250 A (totalling 750 A for the six diodes in three-phase bridge). The cooling system is so arranged that the temperature at the screwed base of the diode can be kept at 120 °C at this load (admissible temperature 110 °C according to the data sheet). On completion of the overload test, the forward and inverse characteristics of these diodes are again recorded, the results being compared with those obtained before the overload test.

These tests confirm that the Brown Boveri diodes rated 200 A at 600 V can be loaded at the rated figure continuously without any fear of harm, as they possess an appreciable reserve capacity, as regards both voltage and current.

Apart from carrying out overload tests, the overload characteristics are also subjected to spot checks, the tested diodes being overloaded to destruction, to check certain points. The importance of knowing the overload characteristic for the various load sequences, especially for planning and designing the protective gear, was amply covered in previous articles.[2, 3]

Operating Experience with Completed Installations

At the beginning of this article it was pointed out that, in addition to careful manufacture and testing of the diodes in the factory, proof of trouble-free operation over a long period is often decisive for a customer's gaining confidence in completely new equipment. This opportunity is taken to thank all those firms who took prototype semiconductor rectifier installations into service, as they greatly assisted the practical introduction of the Brown Boveri diodes. The state of the diodes in these installations is checked by the Company from time to time. Only by doing so is it possible to corroborate the prognoses made regarding the durability of the diodes.

The first semiconductor rectifier installations supplied by Brown Boveri are described below, with special reference to the experience gained with them in service.

Germanium Rectifiers

The very first semiconductor rectifier installation built by Brown Boveri was at the works of Neher & Co., Mels, Switzerland, and was designed for a capacity of 2000 A at 100 V. It is equipped with germanium diodes rated 100 A at 100 V (Fig. 5). The rectifier unit is fed from a 250-kVA variable transformer in Pruneau connection. The voltage provided by the transformer is infinitely variable between 49 and 90 V. The rectifier cabinet contains 48 germanium diodes. In the three-phase bridge circuit employed, each phase has eight diodes in parallel,

[2] See pages 176–92.

[3] See pages 193–208, especially p. 204/5

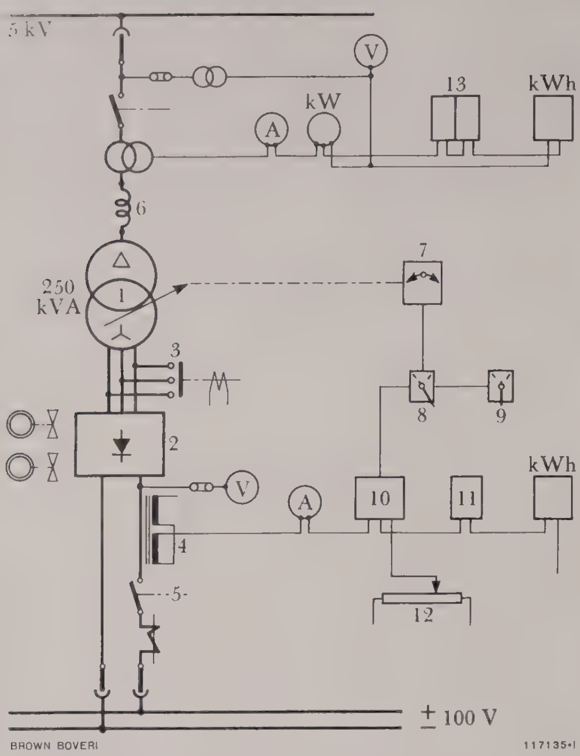

Fig. 5. – Circuit diagram of a germanium rectifier installation rated 2000 A at 100 V

1 = Variable transformer in Pruneau connection
2 = Germanium rectifier unit
3 = Shorting switch
4 = D.C. transformer
5 = D.C. circuit-breaker
6 = Damping choke
7 = Adjusting control
8 = Selector switch (automatic/manual)
9 = Control switch (down/up)
10 = Impulse regulator
11 = Overcurrent relay
12 = Desired-value potentiometer
13 = Overcurrent relays

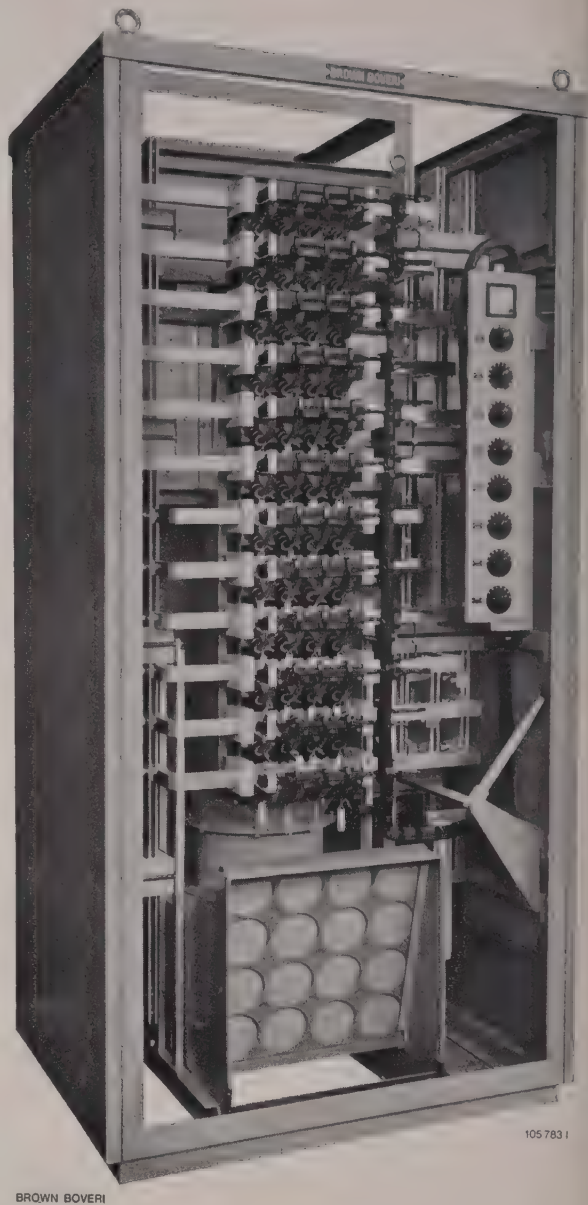

Fig. 6. – Germanium rectifier cabinet rated 2000 A at 100 V

This rectifier is connected as a three-phase bridge. The upper six rows of diodes form the positive pole, the lower six the negative pole. The input from the transformer is applied through the three bars on the right-hand side of the cabinet.

these all being diodes having the same forward coefficient, in order to ensure that the current distribution is correct without resorting to auxiliary means. The maximum current difference between parallel diodes is of the order of ± 15%. To protect the diodes against internal and external short circuits a shorting switch is provided.

Fig. 6 shows the open cabinet of this installation. Visible in the upper part are the twelve rows of diodes, each row having four diodes in parallel. On the right of the unit are the three a.c. busbars, left the d.c. output bars and, at the bottom, the fan used to cool all the diodes. The air for cooling is drawn in through the filter provided.

The installation was commissioned in January 1959 and has been in continuous service ever since. To enable essential work to be performed on the electrolysis baths, the rectifier is switched off once a day. All the germanium diodes supplied with the

original unit are still in service and have thus been in operation for over 24 months. Not one diode has had to be replaced in this period; neither have there been any other stoppages.

In order to obtain performance figures, the diodes are periodically checked and measurements taken. These figures prove that the inverse characteristics of some of the diodes deteriorated slightly between 2000 and 4000 hours, but these diodes were quite stable after 4000 hours. Thus, after over two years, there are no apparent indications of the diodes ageing. This variation in the characteristic has so far only been observed with the germanium diodes; no such effect has been detected with the silicon diodes developed later. It may therefore be anticipated that the new silicon diodes are even more stable than the germanium diodes.

The second Brown Boveri semiconductor rectifier installation was commissioned in June 1959 at the Swiss Soda Works in Zurzach. This installation is designed to produce 10000 A at 300 V. The rectifier operates in parallel with three mechanical rectifiers in an electrolysis plant producing chlorine, the d.c. voltage being 260 V. The circuit diagram of this germanium rectifier unit can be seen in Fig. 7. The 3700-kVA main transformer is fed from the 16-kV supply network through a low-oil-volume primary circuit-breaker. By means of the built-in tap-changer the d.c. voltage can be varied in 30 stages between 140 and 300 V. On the secondary side the transformer has three separate windings, insulated from one another. Each of these windings feeds a rectifier unit in three-phase bridge circuit, each unit comprising one cabinet for the positive pole and one for the negative. On the d.c. side these three sets of cabinets are connected in series.

Each of the six rectifier cabinets contains 108 diodes, i.e. 36 diodes per phase, arranged in four rows of 9, connected in parallel. The average load per diode is thus 96 A. Hence, with a measured deviation of ± 15% in the current distribution, some of the diodes are obliged to carry a maximum of 110 A.

Since this rectifier has to run in parallel with mechanical rectifiers, it is also equipped with automatic current control. For the fine variation between the tappings of the transformer, transductor chokes

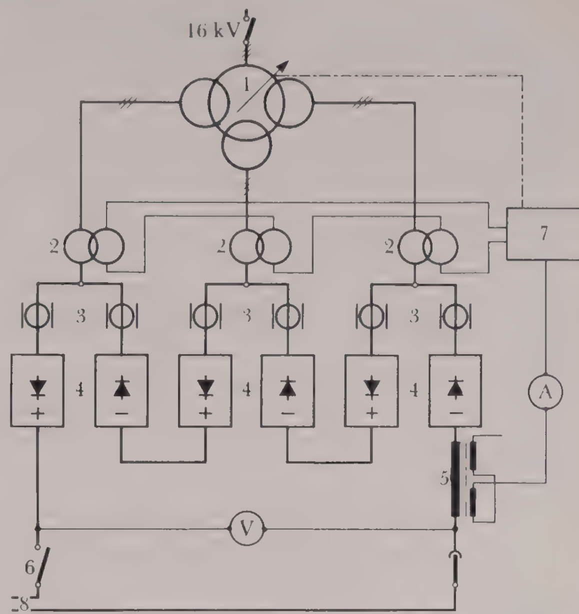

Fig. 7. – Circuit diagram of a germanium rectifier installation rated 10 kA at 300 V

1 = Transformer with on-load tap changer and three secondary windings
2 = Transductor chokes
3 = Reverse-current transformer
4 = Germanium rectifier cabinet
5 = D.C. transformer
6 = D.C. circuit-breaker
7 = Current control equipment
8 = Output to electrolysis baths

The three rectifier units, each for 10 kA at 100 V, are connected in series on the d.c. side

are employed, which are connected between the secondary winding of the transformer and the rectifier cabinet. These consist of premagnetized iron cores placed over the bars connecting the transformer and the rectifier cabinet. To protect the diodes each pair of cabinets contains a shorting switch, which is tripped through reverse-current transformers if a diode breaks down. The installation is protected against external short circuits by a d.c. circuit-breaker.

In order to determine the stability of the germanium rectifier in the event of a fault occurring in the mechanical rectifiers, resulting in the shorting switches tripping, some backfires were artificially produced in the latter rectifiers and the results oscillographed.

These tests showed that the protective gear functioned properly, i.e. the affected mechanical rectifier was disconnected by its own d.c. breaker without affecting the operation of the germanium rectifier.

In this installation the diodes are also periodically checked. These tests yielded the same results as in the plant previously described.

The third installation, for 15000 A at 260 V, which is in operation in a German chemical works, also runs in parallel with four mechanical rectifiers. In contrast to the Zurzach installation, the germanium diodes in this case are arranged in blocks comprising three rows of six parallel diodes, connected in series. The voltage distribution between the series rows of diodes is controlled by parallel resistors and capacitors connected in parallel with the individual rows of diodes. The transformer has two secondary windings, one in delta, the other in star. Each of these windings feeds a 7500-A rectifier unit in three-phase bridge connection, so that the ripple in the supply mains is twelve-pulse. All the 1080 diodes are housed in a pair of cabinets.

Voltage control, protection against backfire by a shorting switch, and overload protection by d.c. breakers are the same as in the Zurzach installation. Confirmatory tests proved that when the shorting switch tripped on one of the mechanical rectifiers or on the germanium rectifier, only the defective unit was selectively disconnected, while the other units continued to operate unchanged.

This installation commenced continuous service in April 1960, since when it has not given the slightest trouble. In September 1960, in one of the rectifier cabinets, one of the three series rows of diodes was deliberately short-circuited. In this way the voltage stress on these diodes was raised by 50%, i.e. to 150 V (PIV). This increased voltage stress has also been satisfactorily withstood so far by the built-in diodes.

Silicon Rectifiers

The first installation to be equipped with the silicon diodes developed in the meanwhile was taken into service in June 1960 in the Chippis aluminium factory, Switzerland. This trial rectifier is fed from the transformer of the first Brown Boveri mechanical rectifier. The installation is rated 8500 A at 400 V and is equipped with two rectifier cabinets containing silicon diodes in bridge connection, the total number being 60 diodes. As control chokes for fine variation of the voltage between the transformer tappings, the comreactors of the mechanical rectifier are utilized.

To protect the diodes against internal short circuits they are each equipped with a special fuse (see page 184/5). Protection against external short circuits is afforded by shorting switches tripped by impulse current transformers.

Ever since it was commissioned, this trial installation has been running in parallel with two mercury-arc rectifiers and a mechanical rectifier, feeding a series of aluminium furnaces at a voltage between 370 and 430 V, the silicon rectifier unit carrying a sustained load of 8000–8500 A.

Fig. 8 shows a recording chart of this installation. It will be observed that, despite the appreciable voltage fluctuation on the d.c. side, the direct current output is kept very constant by the magnetic voltage controller. At point *a* the parallel mechanical rectifier was disconnected by causing an artificial short circuit, whereupon the shorting switch tripped. Until it was switched on again at *b* the silicon unit carried an overload of up to 9500 A. This overload was carried without the least disturbance. Thus a faulty unit can be selectively disconnected without affecting the operation of the others.

The oscillograms in Fig. 9 depict the voltage conditions in this installation. Trace 9a shows the conditions when the d.c. voltage is full on, i.e. about 420 V; traces 9b and 9c, in contrast, with the d.c. voltage reduced to 365 and 340 V, respectively. It can be seen that, in the latter case, the diodes have to withstand an inverse voltage of 600 V at the beginning of the inverse period. This wide range of variation, utilizing the existing comreactors of the mechanical rectifier, which imposes an overvoltage on the diodes, was knowingly accepted in this particular installation, in order to gain information regarding the behaviour of the diodes under such extreme conditions.

Fig. 8. – Recording chart showing the operation of a silicon rectifier running in parallel with mercury-arc and mechanical rectifiers to feed a series of aluminium furnaces

1 = Direct current 2 = D.C. voltage

Despite the severe fluctuation of the voltage in the d.c. supply, the current is kept constant by the automatic regulator. At the point *a* the parallel mechanical rectifier was disconnected. The silicon rectifier took over the momentary overload without any trouble. The mechanical rectifier was switched on again at point *b*.

The diodes are also periodically checked at Chippis. So far not one diode has broken down in service, in spite of the almost continuous overvoltage.

A second silicon rectifier installation was taken into service in October 1960 in a substation feeding the overhead contact wire of the Oberrheinische Eisenbahn-Gesellschaft (OEG) at Mannheim in Germany. This rectifier is housed in one cabinet and is designed for 1250 A at 825 V, with provision for overloading up to 2500 A.[4]

[4] See the article on p. 274–6.

Economic Advantages of Converting Mercury-Arc Installations to Silicon Rectifiers

Particularly favourable conditions regarding the improvement of the efficiency, i.e. reduction of the losses, can be gained in many cases by changing over from existing mercury-arc rectifiers to silicon rectifiers. Brown Boveri were entrusted with the conversion of an installation dating back to 1938, feeding the furnaces of the aluminium works in Martigny,

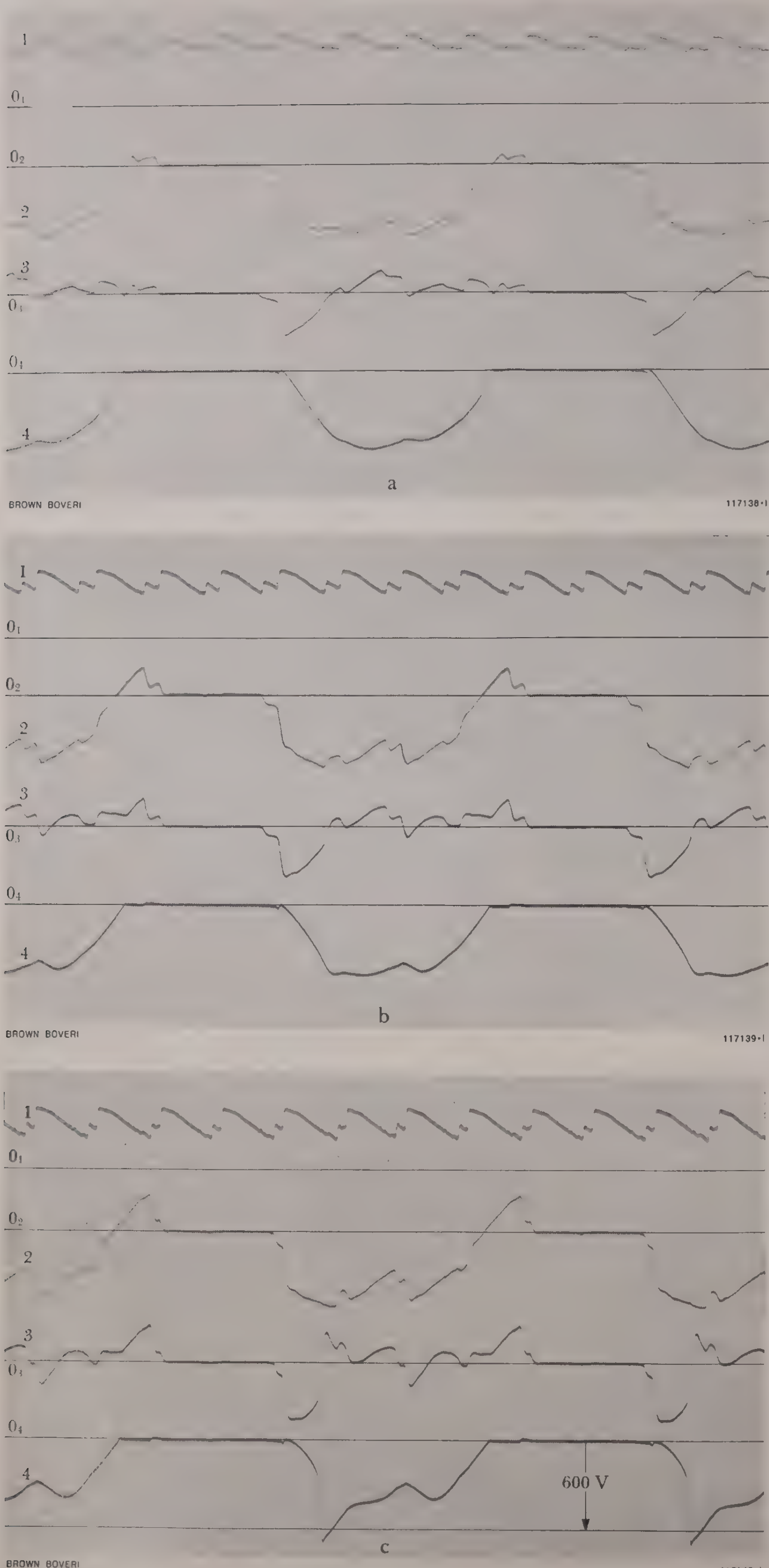

Fig. 9. – Voltage variation in a silicon rectifier rated 8500 A at 400 V, used to feed aluminium furnaces

The oscillogram 9a shows the conditions when the rectifier is at full voltage, while 9b and 9c show the conditions when the voltage is reduced by 12 and 20% respectively. By varying the premagnetization current of the regulating chokes, the output d.c. voltage can be quickly regulated with the consumption of very little control power.

1 = Output d.c. voltage

2 = Voltage between transformer and d.c. busbars

3 = Voltage at the regulating choke

4 = Voltage at the silicon diodes

0_1–0_4 = Zero lines of the oscillograms 1–4

In Fig. 9a:

Direct current	8500 A
D.C. voltage	420 V

In Fig. 9b:

Direct current	8500 A
D.C. voltage	365 V

In Fig. 9c:

Direct current	8500 A
D.C. voltage	340 V

All three oscillograms were recorded on the same transformer tapping, but with different premagnetization currents in the regulating chokes.

Fig. 10. – Silicon rectifier installation in the aluminium works at Martigny, Switzerland, with six silicon rectifiers, each rated 6000 A at 400 V

By replacing six old 18-anode mercury-arc rectifiers by modern silicon rectifiers, the economic performance of the installation was improved to such an extent that the cost of the newly installed equipment were amortized completely within one year. The replacement of the mutators by silicon rectifiers was effected in easy stages. The two mercury-arc rectifiers visible in the background have also been replaced by silicon units in the meantime.

Switzerland.[5] This installation contained three double mutator sets rated 11 500 A at 400 V. Each transformer feeds two 18-anode mercury-arc rectifier sets. The six mutators have been replaced by six silicon rectifier cabinets each rated 6000 A at 400 V (see Fig. 10 and colour plate on the front cover), the existing anode distribution chokes having been replaced by transductor chokes for control purposes. The three double-deck transformers with built-in tap changers and interphase transformers have, however, been retained without modification. The primary switchgear, with airblast breakers for 64 kV, and the whole of the d.c. switchgear was likewise taken over unchanged for the silicon rectifiers. The voltage is still controlled coarsely by a tap changer, whereas for the fine control the premagnetized transductor chokes previously described are employed. Shorting switches are used to protect the diodes against internal short circuits or shorts on the d.c. side.

The advantages of a conversion of this nature will be demonstrated by the economic calculation given below. After the conversion the transformer losses remain exactly the same as before and therefore do not need to be taken into account. Thus it is merely necessary to compare the losses of the actual mutators, including auxiliaries, with those of the silicon rectifier cabinet and its auxiliaries and transductor chokes. Considering an average output of 5000 A per mutator or silicon cabinet, the losses work out as follows:

[5] A. Danz: New mutator plants in the Swiss metallurgical and chemical industries. Brown Boveri Rev. 1944, Vol. 31, No. 4, p. 131–9.

Mercury-arc rectifier

Power loss with arc voltage drop of 27 V at 5000 A	135·0 kW
Power lost in the anode chokes	1·5 kW
Losses of auxiliaries for ignition, excitation, cooling, vacuum pump, control, etc.	3·5 kW
Total losses per mutator	$P_1 = 140{\cdot}0$ kW

Silicon rectifier

Forward and inverse losses with diodes connected in series pairs	11·7 kW
Losses in the transductor chokes	8·0 kW
Losses for auxiliaries, i.e. cooling, control, etc.	2·3 kW
Total losses per silicon rectifier	$P_2 = 22{\cdot}0$ kW
Difference in losses	$P_1 - P_2 = 118{\cdot}0$ kW

Hence the annual saving (considering 365 days operation, with 24 h per day) for the entire installation with 6 sets is given by

$$6 \times 118 \times 24 \times 365 \approx 6{\cdot}2 \text{ million kWh}$$

Hence, if there is an existing contract between the power company and the aluminium plant for the terms under which power is supplied, the conversion allows more aluminium to be produced for exactly the same power consumption. In other words, more furnaces can be fed. Assuming a specific power consumption of about 20000 kWh per tonne of aluminium, it is possible to produce roughly 310 t more aluminium per year after changing over to silicon rectifiers. An economic calculation based on this fact leads to the result that the cost of conversion can be completely amortized within one year.

Conclusions

The experience gained so far with semiconductor rectifiers has proved that the silicon rectifier in particular, owing to its low voltage drop and its high blocking capacity, can command a wide and varied field of applications. Most interesting prospects are afforded by the conversion of existing installations employing mercury-arc rectifiers. In such cases the existing transformer and switchgear can usually be retained unchanged, the cost of conversion being amortized in a very short time as a result of the reduced losses. A prerequisite condition for the general adoption of this new rectifier technique, however, remains the careful manufacture and conscientious testing of every single diode. Operating experience gained so far has shown that Brown Boveri diodes are subject to hardly any ageing and can therefore guarantee reliable service for many years.

(KME) H. BLATTER

THE USE OF SILICON RECTIFIERS WITH VARIABLE-SPEED DRIVES OF MEDIUM POWER

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681.624-83:621.314.632:546.28

A brief description is given of a variable-speed drive for a printing press employing a 50-hp d.c. motor with silicon diodes as the rectifiers and magnetic amplifiers as the correcting elements.

IT is a generally accepted fact that the d.c. motor is an ideal means of handling a wide speed range at a high efficiency. Without going into the theory of the performance of the d.c. machine in detail, it may be mentioned, for the sake of completeness, that at constant excitation, the speed may be varied by altering the armature voltage. In addition, the speed range at constant power can be extended in the upward direction to a maximum of 1:3 by field weakening.

The oldest circuit for a wide speed range is the well-known Ward-Leonard circuit. The current required by the d.c. motor is obtained from a generator, which is usually driven by a three-phase motor running at constant speed. The speed of the d.c. motor, disregarding voltage drops, is then proportional to its armature voltage and can be varied by altering the excitation of the generator, which of course results in its voltage varying. In order that the speed may correspond sufficiently accurately to the set value, a means of closed-loop control must be employed. The speed is measured by a tacho-generator, which produces a voltage proportional to the motor speed, and this voltage is compared with the desired-value voltage, set to correspond to the desired speed. The difference between these voltages is amplified, the output voltage of the amplifier being applied to the exciter winding of the generator in the desired sense. The speed drop is reduced by the closed-loop gain attained by the control system.

An obvious solution is for the voltage of the Ward-Leonard generator to be replaced by that of a grid-controlled rectifier, the speed regulator acting on the grid control set. Employing this principle, drives have already been supplied for powers up to several thousand kilowatts. For high powers grid-controlled mercury-arc rectifiers are normally used, for low powers, up to about 10 kW, thyratrons.

A logical conclusion now would be to utilize the newly created semiconductor diodes for variable-speed drives. But, unfortunately, these rectifiers cannot be controlled yet. One is therefore compelled to produce a variable, and if possible controllable, voltage with the aid of supplementary control elements. There are several methods of doing this, the suitability of which varies from one to another. For example, the rectifier set may have a variable-voltage transformer, such as the infinitely variable plunger-type transformer, connected in series. The output voltage is then varied by changing the alternating voltage supplied to the rectifier. To effect closed-loop control, the variable transformer has to be actuated by a servomotor.

A severe disadvantage of this system of control is the presence of mechanically moving parts, and their inherent inertia. For this reason a change has been made to magnetic amplifiers, which nowadays can be built for powers up to about 200 kW. A magnetic amplifier consists of an iron core with several separate windings. One of these is the power winding, which is connected in series with the load circuit, for which it acts as a variable inductance. A further winding acts as the control winding, as may be seen in Fig. 1. At the bottom $U\sim$ denotes the a.c. supply network; R_B is the load, which has to be fed at

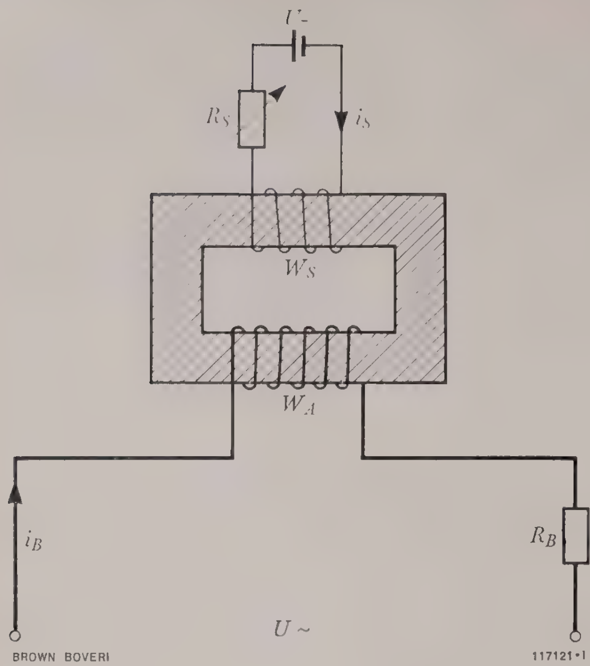


Fig. 1. – Principle of the single-core magnetic amplifier

W_A = Power winding
W_S = Control winding
R_B = Load resistance (burden)
i_B = Load current
i_S = Control current
R_S = Variable control resistance
$U-$ = Source of d.c. control current
$U\sim$ = Supply mains

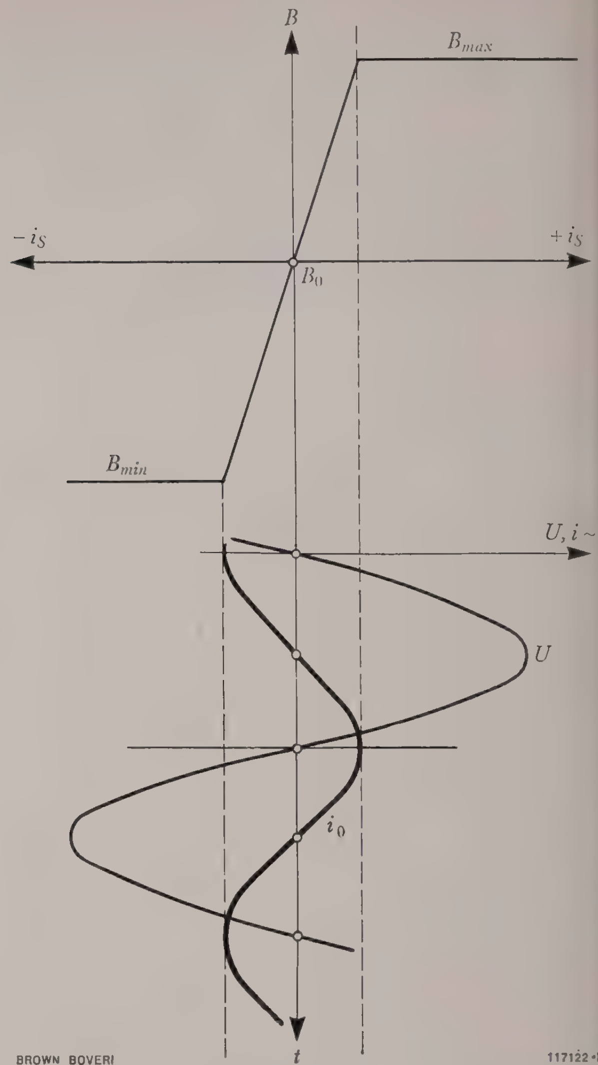


Fig. 2. – Characteristics of the power winding

Upper curve:

$B_{min} \ldots B_0 \ldots B_{max}$ = Ideal magnetization curve of the core
i_S = Control current (ampere-turns)
B = Flux density

Lower curve:

U = Applied a.c. voltage $U = f(t)$
i_0 = Magnetization current

variable voltage, W_A is the power winding of the magnetic amplifier. W_S is the control winding carrying the control current i_S, which in this case can be varied with the resistor R_S. In a closed-loop control circuit the controller supplies the control current, so that there is no resistor with a sliding contact.

The power winding is dimensioned so that the applied supply voltage produces a magnetic flux which passes through the entire magnetization curve between the two saturation bends, as shown in Fig. 2. Plotted in the upper half of the diagram, from left to right, is the control current or ampere turns. The magnetization curve is an angular S-curve running from B_{min} to B_{max}. The voltage applied to the power winding produces a flux which, as already mentioned, varies between B_{min} and B_{max}. The corresponding magnetization current i_0 is then between the broken lines. Owing to the steepness of the magnetization curve, this current is very small; hence there is only a small voltage at the load. In the case of a power stage for 50 kW this no-load current amounts to about 2 A, compared with 120 A at full load. However, if the core is premagnetized by a control current, as seen in Fig. 3, it reaches saturation in the course of one half-wave. The magnetization curve with its saturation bends is again plotted at the top. This diagram differs from the previous one in that

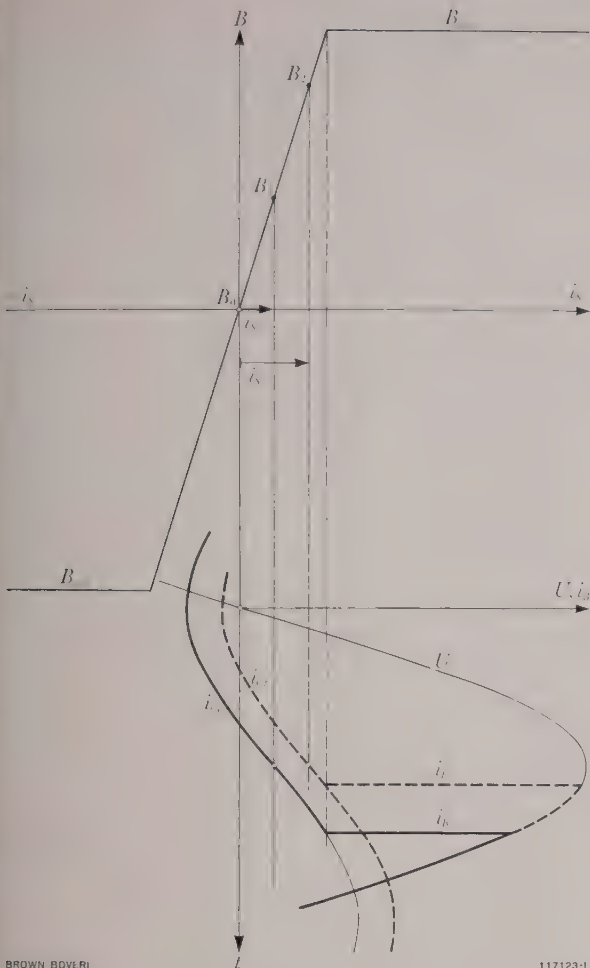


Fig. 3. – Core of the magnetic amplifier partly premagnetized

Upper curve:

B_1, B_2 = Core partly magnetized by control current i_{S1}, i_{S2}

Lower curve:

i_{B1}, i_{B2} = Load current, which jumps to a value corresponding to the momentary value of the voltage U and the resistance of the burden

i_{01}, i_{02} = Magnetization current with new zero line through B_1, B_2

the core is premagnetized to a flux density B_1 by the current i_{S1}. The magnetizing current can now only follow the original curve for a small part of the way; then the core reaches the saturation point and no further change in flux is possible. At this moment the impedance of the power winding diminishes to the resistance of the copper and the stray inductance. The current jumps abruptly to a value which corresponds to the momentary value of the voltage and the load resistance. Consequently a load current

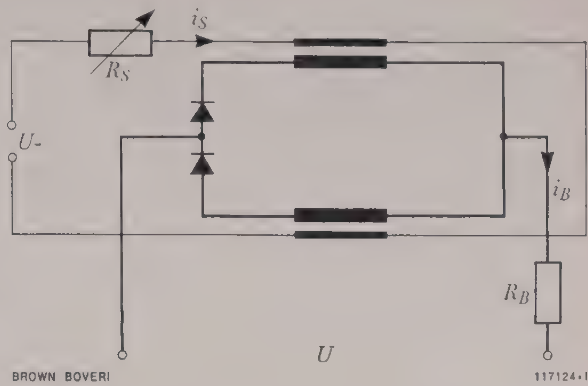


Fig. 4. – Magnetic amplifier with two cores and a.c. output

R_B = Load resistance (burden)
i_B = Load current
i_S = Control current
R_S = Variable control current
U_- = Source of d.c. for control
$U\sim$ = Supply mains

following the heavy line is produced $(i_{01} - i_{B1})$. The broken curve $i_{02} - i_{B2}$ shows the effect of heavier load on the magnetic amplifier. During the corresponding part of the half-wave the load circuit experiences the full supply voltage. Depending on the magnitude of the control current, the half-wave will be cut to a greater or lesser extent. Thus a means is provided of effecting an appreciable change in the output current with only a small change in the control current. Hence this system is, in effect, a power amplifier. The illustration is severely idealized and is merely intended to give an impression of the effect of "cutting" the half-wave.

Frequently a circuit is employed, having two cores and two rectifiers (Fig. 4). The latter only conduct during one half-wave each, via the respective core. Thus each core is separately premagnetized by the d.c. component of the output current. This is a self-saturating circuit with a high gain resulting from the feed-forward through the rectifiers. The circuit illustrated supplies alternating current with cut half-waves to the load circuit.

A circuit with a d.c. output is shown in Fig. 5. On the left are the saturation rectifiers, on the right the load circuit. The rectifiers on the right ensure that the current always flows in the same direction through the load. It will be seen that these four rectifiers form a single-phase bridge circuit, two limbs of which,

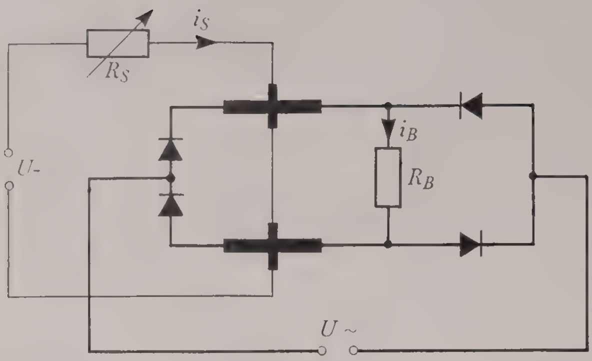


Fig. 5. – Magnetic amplifier with d.c. output

Notation as for Fig. 4

however, contain the power windings of the magnetic amplifier. The characteristic of a magnetic amplifier of this kind may be seen in Fig. 6, which shows that even when the control current is zero, an appreciable output current flows. By applying a negative control current it is possible to block the amplifier to an appreciable extent. The resultant residual current is caused by the magnetization current and the fact that the characteristic increases again towards the left, due to the inverse current of the rectifiers. In the silicon rectifiers the latter is negligibly small. By means of a third winding on the cores, known as the premagnetization winding, a constant direct current can be made to displace the characteristic horizontally by any desired amount, so that the whole characteristic can be followed with a control current which is only positive and increasing.

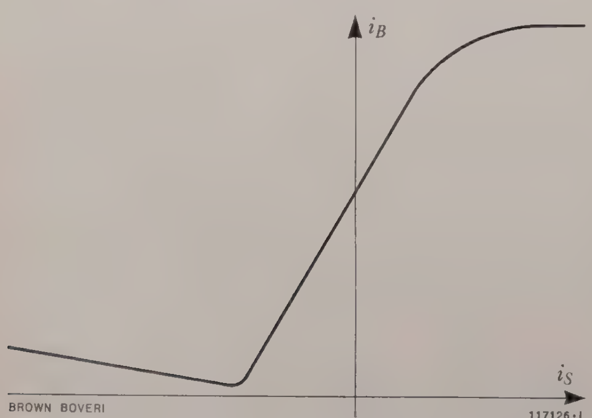


Fig. 6. – Characteristic of a magnetic amplifier as in Fig. 5

i_S = Control current
i_B = Load current

Fig. 7 shows the magnetic amplifier circuit for a motor rating of 50 hp. To control higher powers it is preferable to employ a three-phase magnetic amplifier circuit. In accordance with the single-phase bridge circuit referred to above, this arrangement can be based on the three-phase bridge circuit. Each of the three supply phases R, S, T of the network is split between a pair of opposed rectifiers, three of which are combined to form the positive pole and three the negative. Each rectifier limb is allocated a power winding on a core of its own. Each pair of cores is a constructional unit; they form a magnetic amplifier with a common control winding. An amplifier of this kind for a single-phase output of 16 kW is depicted in Fig. 8. Windings can be seen at the front and at the rear. Each winding consists of the power winding with a correspondingly heavy cross-section, above which is the premagnetization winding and the control winding, of smaller cross-section. The two cores are separated by a small gap in the middle of the unit; the latter cannot be seen in the photograph owing to the bolted fixings. The cores are combined to form a unit by strong angle-iron members. The material used for the cores is cold-rolled grain-orientated silicon-steel sheet, which has been tempered by a special heat-treatment process after stamping, before the stampings are stacked. The terminals are situated at the forward end. The entire transductor can be pushed into a switchgear cabinet on its rollers. Three such units are required. In this form the units are intended for enclosure in a section of a switchboard; for open-type installations they should be fitted with a casing, as shown in Fig. 9.

The power windings are connected directly to 380 V. The output voltage of the magnetic amplifier is applied via contactors, interpole and compound windings, to the armature of the d.c. motor, whose field is excited from the mains via a special rectifier. Depending on the magnitude of the control current through the series-connected control windings, the amplifier increases its voltage and the motor runs at the proportional speed.

Considering the voltage drops in successive elements, it is evident that a simple system like this must exhibit quite an appreciable drop in speed as the load increases. In order to avoid this, a controller must be employed, shown schematically as item 16

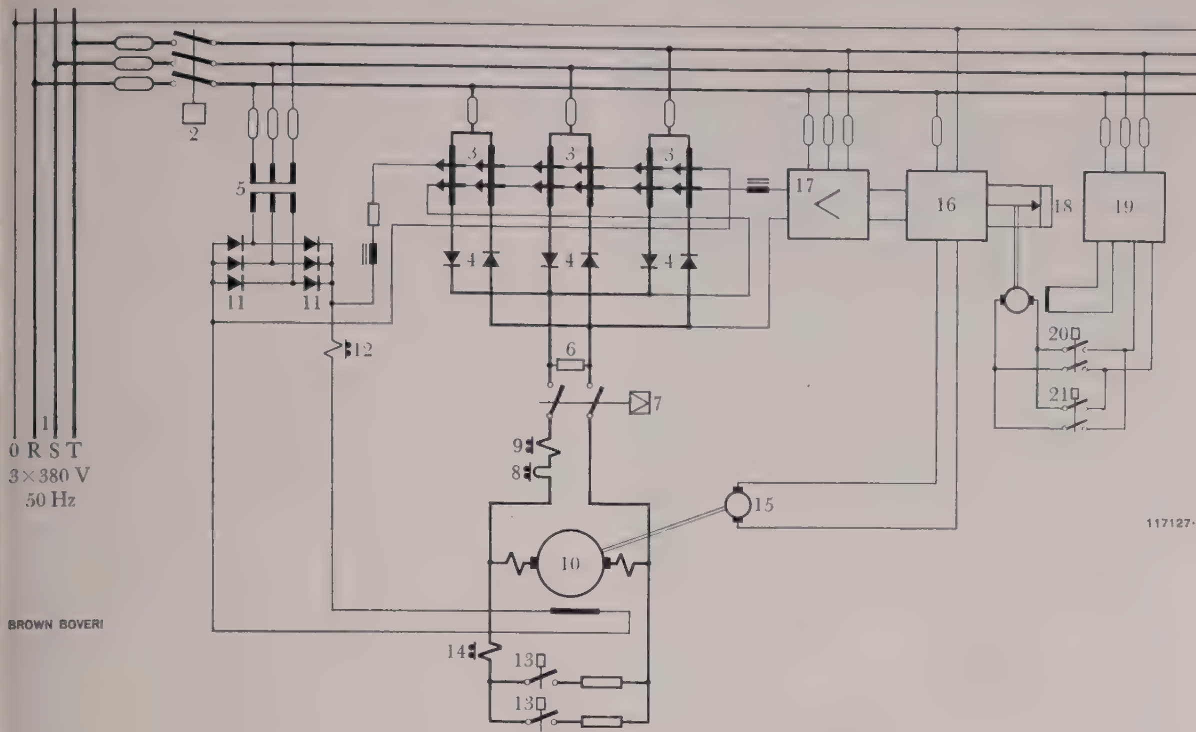


Fig. 7. – Circuit diagram of a three-phase magnetic amplifier controlling a motor rated 50 hp

1 = Supply mains
2 = Main switch
3 = Three-phase magnetic amplifier
4 = Three-phase rectifier with 6 semiconductor diodes
5 = Premagnetization unit for 3
6 = Base-load resistor
7 = Motor contactor
8 = Thermal protection
9 = Overcurrent protection
10 = D.C. motor, 50 hp
11 = Exciter rectifier
12 = Relay supervising field current
13 = Braking contactor
14 = Relay for second braking stage
15 = Tacho-generator
16 = Transistorized controller
17 = Intermediate amplifier with transistorized preliminary stage and magnetic output amplifier
18 = Desired-value potentiometer
19 = Power pack for 18
20 = Relay for "Faster"
21 = Relay for "Slower"

in Fig. 7. This block contains the controller proper and a supplementary circuit giving the controller a certain response, so that control may be stable. It also contains a power pack for feeding the amplifier and the element used for setting the desired value, in the present case a motor-driven potentiometer, designed to enable the driven machine (in this example a printing press) to run up slowly. The controller, with its stabilizing elements and power pack, consists of standardized "building-blocks" belonging to the Brown Boveri electronic system (power range).[1]

Obviously the power output from a small printed circuit, corresponding to 15 V and 5 mA, at full output, is by no means capable of controlling the power amplifier. For this reason an intermediate amplifier was developed, which is also denoted by a block in the above circuit diagram. Actually it consists of two amplifiers, a transistorized preliminary stage and a three-phase magnetic amplifier stage, the former having an input of 15 V and a control current

[1] H. Brändle, K. Stahl: Fundamental Aspects of the Brown Boveri Electronic System. Brown Boveri Rev. 1960, Vol. 47, No. 10/11, p. 661–70.

T. Ernst: Design Principles of the Brown Boveri Electronic System. Brown Boveri Rev. 1960, Vol. 47, No. 10/11, p. 670-5.

R. Zwicky, M. Syrbe: The Brown Boveri Electronic System—Closed-Loop Control. Brown Boveri Rev. 1960, Vol. 47, No. 10/11, P. 676–81.

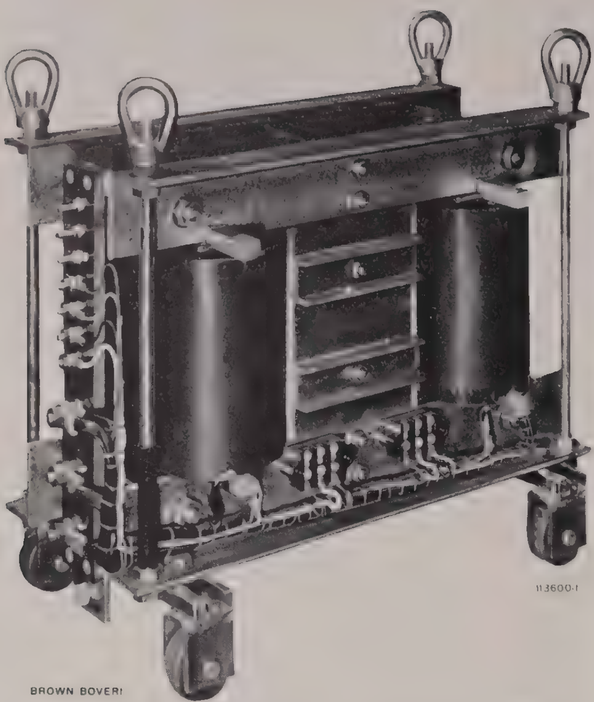


Fig. 8. – Magnetic amplifier unit for a single-phase output of 16 kW

Mounted on rollers or enclosure in a cabinet.

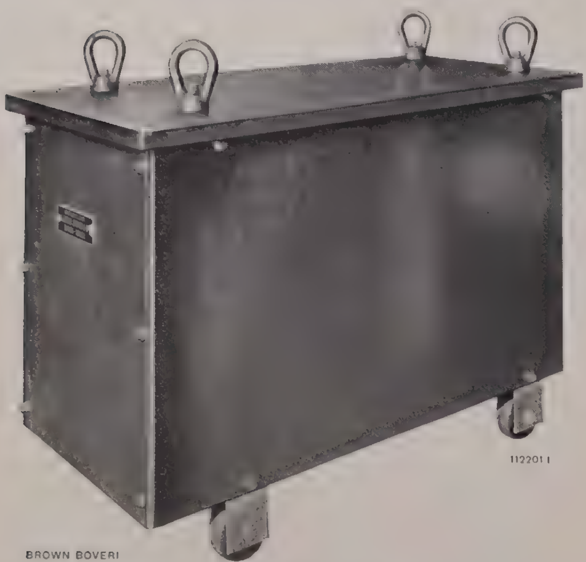


Fig. 9. – The same magnetic amplifier as in Fig. 8

but in a casing for installation in an open room.

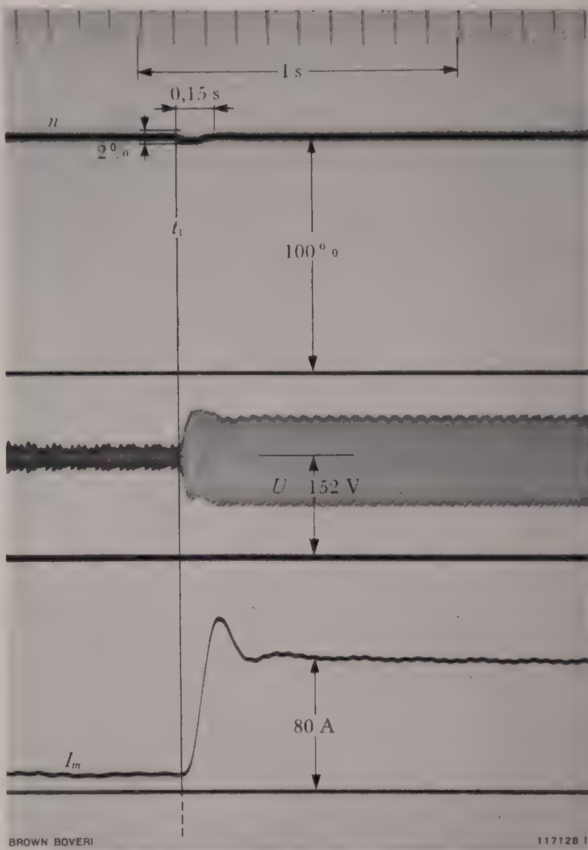


Fig. 10. – Oscillogram of a full-load surge

n = Motor speed 1000 rev/min = 100 %
t_1 = Moment at which the braking generator was switched on
I_m = Motor current
U = Terminal voltage of the motor

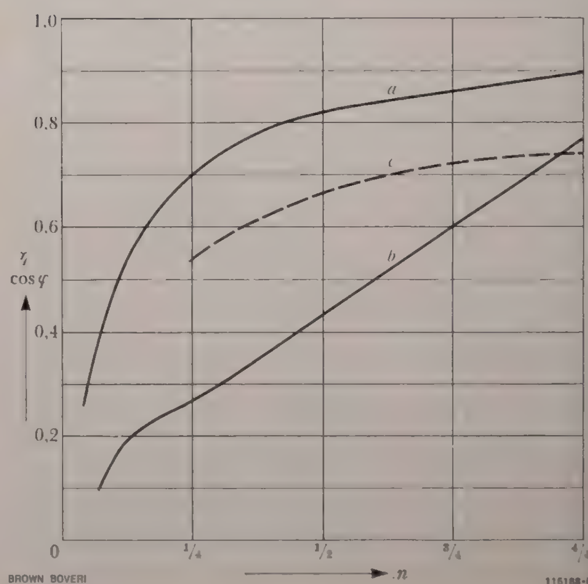


Fig. 11. – Efficiency and power factor as a function of the motor speed at constant torque

a = Efficiency η of a drive controlled by magnetic amplifier
b = Power factor $\cos\varphi$ belonging to a
c = Efficiency of a Ward-Leonard set
n = Motor speed

of 1 mA, the latter an output power of 400 W. This power is sufficient to control the three-phase output stage.

From the circuit diagram in Fig. 7 it can be seen that the output voltage of the magnetic power amplifier is introduced into its control circuit, i.e. in opposition to the output voltage of the intermediate amplifier. Only the difference between these two voltages produces a corresponding control current. This negative feedback forms an inner control loop, which effects a close approximation of the output voltage to the characteristic of the intermediate amplifier. Since the output stages do not have laminations of high-grade steel with such an angular magnetization curve, a straight-line characteristic cannot be expected. However, in the manner described, it is possible to achieve an overall characteristic corresponding to that of the intermediate amplifier, which is made of high-grade toroidal cores. Thus constant gain can be obtained over the entire control range.

On throttling back, for instance due to a reduction in the desired value, the motor runs out in accordance with its inertia and friction. Here the great advantage of regeneration is lost, as afforded without any assistance by the Ward-Leonard drive; consequently, if rapid braking is required, energy must be dissipated in braking resistors. The braking process obeys an exponential function, i.e. the lower the speed, the weaker the effect. Therefore it is often necessary for a second stage to be provided, which is cut in at the moment the braking current of the first stage drops below a certain value set on a suitable current-sensitive relay.

As a result of this control system the drive can maintain its speed to an accuracy of 1 %, referred to its rated speed, for all changes of load between no-load and full load. The correction of a full-load surge in the oscillogram (Fig. 10) exhibits a very small area. This good result may be attributed to the extremely rapid response.

The efficiency of the installation is better than that of the Ward-Leonard set. The curves in Fig. 11 are plotted against the speed at constant torque. From the uppermost curve it is apparent that the efficiency of the magnetic amplifier alone is very high.

With regard to the power factor, however, the situation is rather different. It is inherent in the nature

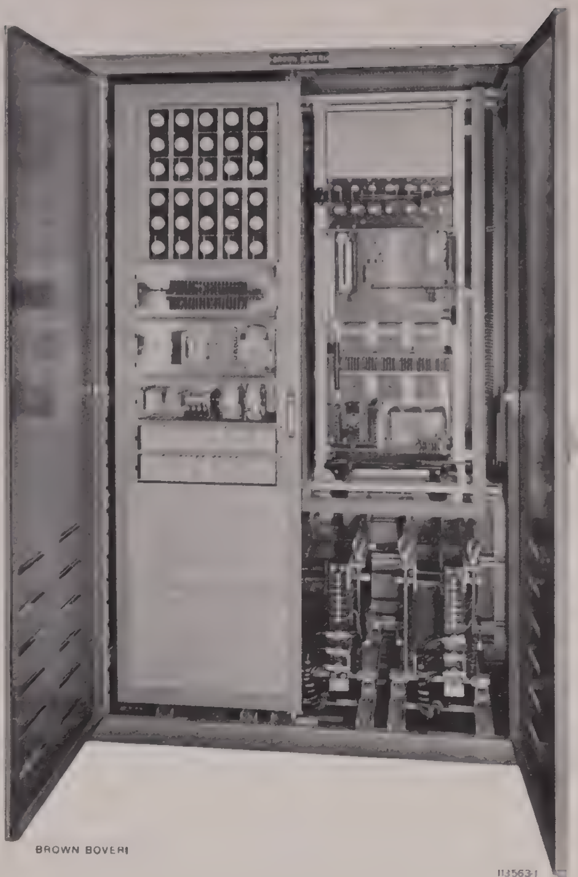


Fig. 12. – Cabinet containing the magnetic amplifier and control gear for a 50-hp variable-speed d.c. drive

of the magnetic amplifier that the power factor should be lower than that of the induction motor driving the Ward-Leonard generator. Theoretically the power factor curve of a controlled rectifier is a straight line from unity at full load, and passing through zero. In practice the residual inductance of the magnetic amplifier causes the curve to begin in the region of $\cos \varphi = 0{\cdot}77$. Then, owing to the active power losses, it runs slightly above the hypothetical straight line through the origin. On account of the high efficiency of the installation this does not make very much difference to improvement of the power factor. The remaining auxiliaries are not included in these remarks.

The layout of the cabinet containing the control gear for the above 50-hp drive can be seen in Fig. 12.

(KME) H. G. MEYER

THE BROWN BOVERI CONTROLLED SILICON RECTIFIER CS 100

621.382:621.316.5

With the introduction of the controlled silicon rectifier, or silicon thyratron as it may be termed, the field of application of the controllable semiconductor has been extended far beyond the limits set by the transistor. The article describes the functions of the silicon thyratron, taking the Brown Boveri type CS 100 as an example; this is a controlled rectifier with a mean rated current of 100 A d.c.

WHEN THE FIRST controllable semiconductor element, the transistor, entered the technical field about ten years ago, it seemed as though its applications were restricted to the sphere of low currents at low frequencies. As a result of the immense effort which went into the continued development, it soon became possible to extend their application to higher frequencies and powers. Here higher powers implies roughly 50 to 1000 W. The employment of the transistor as a control device for powers above about 1 kW has to contend with fundamental problems, so that up to the present it was necessary to employ conventional devices, such as rotating machines, gaseous discharge tubes and magnetic amplifiers. Only about two years ago, when the first controlled silicon rectifier was brought out in the United States, did it become possible to extend the specific advantages of semiconductor elements—low voltage drop and hence high efficiency, no starting or heating time, rapid response and compactness—to the range of powers from 1 kW to over 100 kW.

On account of the close resemblance between its current-voltage characteristic and that of gaseous discharge tubes, the controlled silicon rectifier is sometimes referred to as the silicon thyratron. As regards its current and voltage data it is not subject to the same restrictions as a power transistor, but is comparable with the silicon diode. It is thus possible to manufacture elements with rated currents of about 100 A (mean d.c. value) at inverse voltages of several hundred volts, as will be demonstrated below, taking the Brown Boveri silicon thyratron type CS 100 as an example.

Apart from facilitating the logical replacement of conventional elements, the advantages of the above controlled silicon rectifier enable it to be utilized for new applications. An example is the conversion of small d.c. voltages into alternating voltages, which are technically easier to evaluate, achieving a high efficiency of conversion; the source of d.c. voltage may, for instance, be a thermo-electric generator.

Principle of the Controlled Silicon Rectifier

The internal construction of the active part of a controlled rectifier comprises a four-layer pnpn structure. To explain its electrical action we may start from the psn junction, the arrangement and characteristic of which are repeated in Fig. 1.[1] When the polarity of the anode is negative, the pn junction blocks up to its breakdown voltage U_{D1}. In the opposite case the s zone—here considered to be n-conducting—is flooded with charge carriers of both signs, namely electrons from the highly doped n^+ part and holes from the highly doped p^+ part, and thus becomes a good conductor.

The four-layer element in the silicon thyratron may be imagined to consist of the above psn junction, in which the s_n zone has been replaced by a further pn junction (Fig. 2). If a negatively polarized voltage is applied to the anode of an element of this nature, there is no change with respect to the psn junction in Fig. 1; the pn junction 1 blocks with a breakdown voltage U_{D1}. Junction 2 is in the forward direction, junction 3 in the inverse direction, hence the entire inverse behaviour is governed by junction 1. If the anode is positive relative to the cathode, the junc-

[1] See the article on p. 169–75 of this issue.

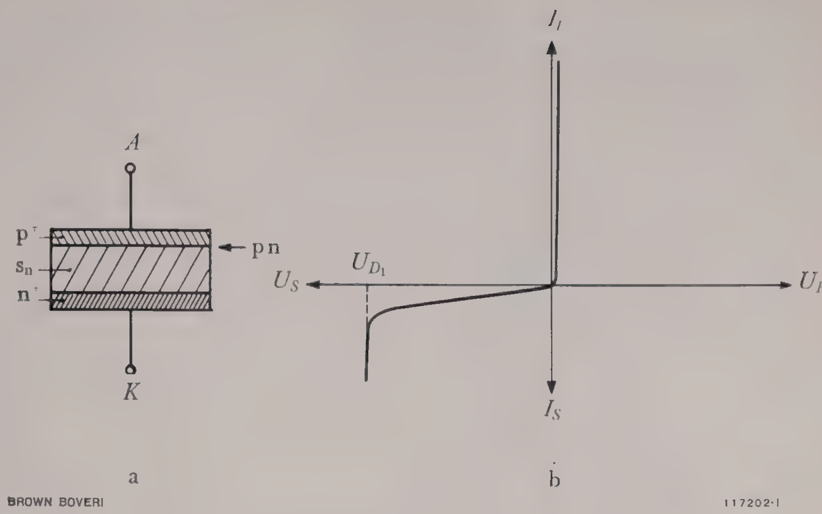


Fig. 1. – Arrangement of a psn junction

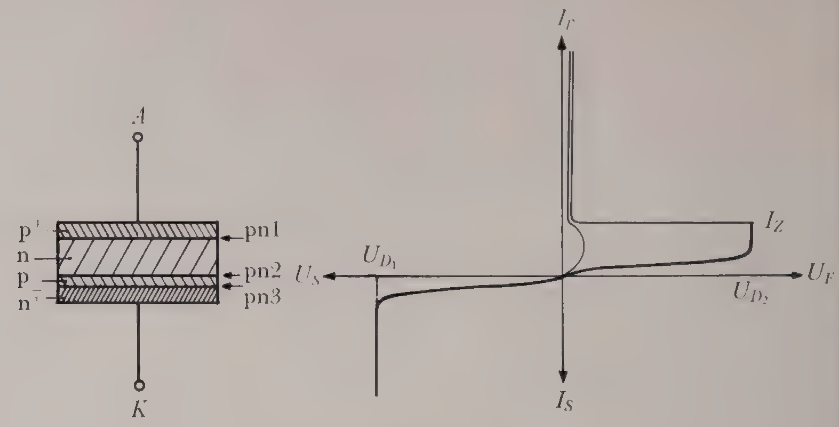
a: psn crystal
- p+ = Highly doped boundary zone, p(hole)- conducting
- sn = Weakly doped intermediate zone, n-conducting
- n+ = Highly doped boundary zone, n (electron)-conducting
- A = Anode
- K = Cathode
- pn = Location of the pn junction

b: Current voltage characteristic
- U_F = Forward voltage
- I_F = Forward current
- U_S = Inverse voltage
- I_S = Inverse current
- U_{D1} = Breakdown voltage in inverse direction

tions 1 and 3 are now in the forward direction, but junction 2 blocks up to its breakdown voltage U_{D2}. Owing to the symmetry of the arrangement U_{D2} must be equal to the breakdown voltage in the inverse direction, provided possible superficial effects are disregarded. In contrast to the inverse direction, however, as soon as the breakdown voltage U_{D2} is exceeded and the current begins to flow, the element "fires", i.e. the blocking resistance, which had hitherto been high, now disappears and there remains a small forward resistance, comparable with the forward resistance of the psn rectifier (characteristic in Fig. 2b, part where $I_F > I_Z$).

The following effects are responsible for the triggering of this firing action. The steep rise of the inverse current occurring when the limit voltage U_D is exceeded is caused by the multiplication of the charge carriers in the strong acceleration fields of the blocking zone of the pn junction. But if the inverse current of junction 2, blocking alone, increases, this results in an injection of charge carriers through the junctions polarized in the forward direction, i.e. electrons from the n^+ zone and holes from the p^+ zone. If the electrons injected at the pn junction 3, by diffusion, reach the still blocking junction 3, the inverse current of the latter is increased even more—known as the transistor effect—resulting in increased injection, and so on. This produces an avalanche which leads to the blocking effect of junction 2 being cancelled altogether. The fired silicon thyratron largely resembles a psn junction in the forward direction, as it consists of two highly doped boundary zones and an intermediate zone flooded with charge carriers.

Since the inverse current of a pn junction can never be equal to zero, owing to the thermionic generation of charge carriers, but always possesses a finite value, even though this may be very small, the firing process described above would take place at any small voltage, i.e. no further blocking action would be possible in the forward direction. However, this is where an effect experienced with silicon becomes very useful; it is well known from silicon transistors, where it is regarded as quite a drawback. This is the dependence of the gain α on the emitter current, namely the increase in α with rising emitter current. Transferred to the controlled rectifier this means that, at low current in the junctions 1 and 3 polarized in the forward direction, hardly any electrons are injected from pn_3 or holes from pn_1, and therefore no increase takes place in the inverse current of pn_2. A certain minimum current I_Z (cf. Fig. 2b) is needed to initiate firing. At the same time it becomes possible for the element to fire at a smaller voltage than U_{D2}. For this



BROWN BOVERI a b 117203-I

Fig. 2. – Arrangement and characteristic of a pnpn element

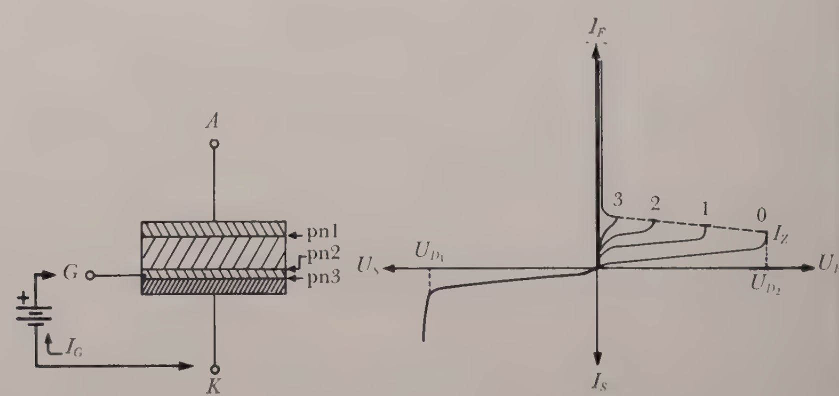
a: pnpn crystal
p+ = Highly doped p-conducting boundary zone
n = Weakly doped n-conducting zone
p = Moderately doped p-conducting zone
n+ = Highly doped n-conducting boundary zone
A = Anode
K = Cathode

b: Current-voltage characteristic
U_F = Forward voltage
I_F = Forward current
I_Z = Firing current
U_S = Inverse voltage
I_S = Inverse current
U_{D1} = Breakdown voltage in inverse direction
U_{D2} = Breakdown voltage in forward direction

The forward characteristic is split into two branches; the outer refers to the increasing current after firing, the inner to decreasing current at the end of the half-wave.

it is merely necessary to raise the inverse current above the value I_Z by an external influence, e.g. by exposure to light of sufficiently high intensity. The technically more important method, however, is to connect a contact, known as the gate connection, to the p zone for instance (cf. Fig. 2 a), as shown in Fig. 3.

If now a voltage is applied to the gate, making it positive with respect to the cathode, electrons are injected into the p (gate) zone from the cathode, in addition to the anode-cathode current, i.e. the inverse current of junction 2, thus raising the gate zone above the firing current I_Z. Since the inverse current



BROWN BOVERI a b 117204-I

Fig. 3. – Arrangement and characteristic of the silicon thyratron

a: pnpn crystal with gate connection, shading as in Fig. 2
pn 1 = pn junction 1
pn 2 = pn junction 2
pn 3 = pn junction 3
I_G = Gate current
G = Gate
A = Anode
K = Cathode

b: Current-voltage characteristic, notation as for Fig. 2
0 = Gate current $I_G = 0$
1 = „ $I_G = I_{G1} > 0$
2 = „ $I_G = I_{G2} > I_{G1}$
3 = „ $I_G = I_{G3} > I_{G2}$

a b

Fig. 4. – Prototype Brown Boveri silicon thyratron type CS 100 for a mean direct current of 100 A

a: General view of the element b: Close-up of the gate connection inside the cathode pin

of a pn junction in silicon is not a pure saturation current, but also grows with increasing voltage, above all, as the result of internal acceleration fields, a smaller gate current is required for firing at high voltages than at low. This state of affairs is illustrated by Fig. 3b. The characteristics 1, 2 and 3 in the forward direction are therein referred to as an alteration in the gate current. By increasing the gate current further it is possible to cancel the blocking action in the forward direction altogether; then the characteristic of the silicon thyratron corresponds exactly to that of an ordinary diode. Once firing has taken place, the gate loses its capacity for control, exactly like the grid of a conventional thyratron. For extinction the current must drop below a certain minimum value, known as the holding current, thereby reducing the anode voltage practically to zero.

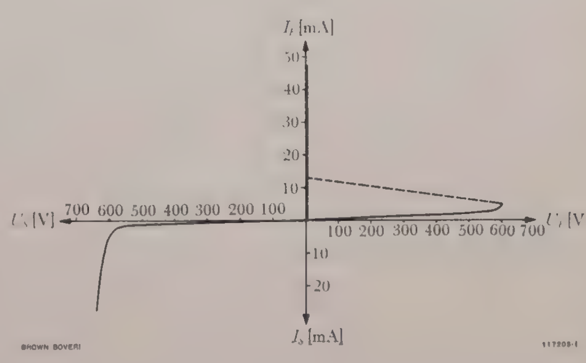


Fig. 5. – Current-voltage characteristic of a CS 100 silicon thyratron

U_F = Forward voltage (in V)
I_F = Forward current (in mA)
U_S = Inverse voltage (in V)
I_S = Inverse current (in mA)

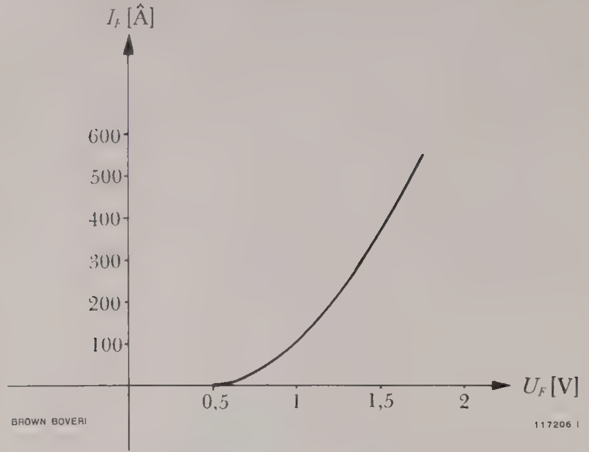


Fig. 6. – Forward characteristic of a CS 100 silicon thyratron in the fired state

U_F = Forward voltage (in V)
I_F = Forward current (in A)

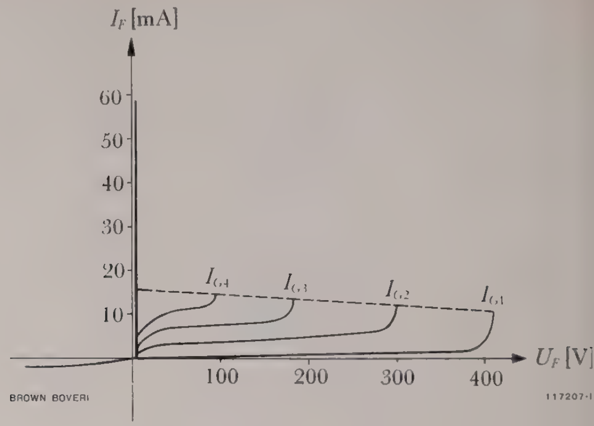


Fig. 7. – Example illustrating the variation of the firing voltage with changing gate current

U_F = Forward voltage (in V)
I_F = Forward current (in mA)
I_G = Gate current

The conditions imposed on manufacturing techniques in order to obtain optimally operating controlled silicon rectifiers are extremely severe, especially when elements for heavy current are involved. For example, inhomogeneity in the gate zone (p zone between junctions 2 and 3 in Fig. 3), i.e. a narrow point due to uneven penetration of the n^+ zone (cathode), can lead to the element firing at a very low voltage, or to its being in a permanently firing state. On the other hand, if the gate zone were too broad throughout, in the fired state, injection into the n zone would be inadequate and this would lead to intolerably high voltage drops in the forward direction. This, when compared with a diode, whose manufacture is considerably simpler, explains why the price of the controlled silicon rectifier is several times that of a diode of the same rating.

The Silicon Thyratron type CS 100

The practical design of a silicon thyratron closely resembles that of a power diode, as illustrated in Fig. 4 of the article on the high-power diode type DS 200 (see page 173). Of course the same conditions with regard to good current conduction and dissipation of the waste heat have to be observed. A point which needs special attention in the controlled rectifier is that at temperatures above about 140 °C inside the element, not only do the inverse losses rise rapidly, but there is also a severe decrease in the breakdown voltage in the forward direction U_{D2}, in other words, when the element is too hot, it can lose its controllability. This point is stressed again to underline the necessity for good dissipation of the waste heat. For this reason the same body is used for the silicon thyratron CS 100 as for the diode DS 200 (Fig. 4a). The sole difference is the insulated introduction of the gate connection. This is mounted coaxially in the cathode pin (Fig. 4b). The provisional data of the unit are: Mean direct current 100 A at service inverse voltages up to 300 V. A typical characteristic is reproduced in Fig. 5, for the case of blocking in either direction, i.e. with zero gate current, while Fig. 6 shows the forward characteristic in the fully fired state.

The gate currents needed for firing are very low, compared with the load current, and range from about 5 to 100 mA. The decrease in firing voltage with increasing gate current up to full firing is shown in Fig. 7.

The silicon thyratron CS 100, having an approximate power of up to about 15 kW per element, permits the field of applications of controlled semiconductors to be extended to a power range which, until now, was confined to the conventional elements. Its specific advantages justify the assumption that this new element will in due course become very important, above all for the control of power circuits.

(KME) E. WEISSHAAR

THE SILICON THYRATRON AS CORRECTING ELEMENT IN CONTROL CIRCUITS

621.382:621.316.7

For use in control circuits silicon thyratrons are combined with suitable auxiliary elements to form sub-units. These may be employed as correcting elements for powers up to 100 kW. The present article briefly outlines their design, properties and applications.

A NEW ELEMENT is now available for control purposes, in the form of the semiconductor thyratron, which possesses a number of exceedingly useful properties. Like the controlled gaseous discharge valves—mutators and mercury-vapour thyratrons—the passage of current through the controlled silicon rectifier can be released by low-powered pulses. The application of a control current in the form of pulses to the gate of the silicon thyratron has exactly the same effect as the grid control pulses of the mutator or thyratron proper. In consequence, the circuit arrangements obtainable are fundamentally the same.

For the employment of the silicon thyratron in control circuits two arrangements have been standardized, in which the thyratrons are combined with the necessary auxiliary elements to form a sub-unit, or building block. The smaller of these has a power rating of 7·5 kW, the larger, which is equipped with Brown Boveri high-power silicon thyratrons, can handle 50 kW. By connecting these units in series and parallel it is possible to cover all powers up to about 100 kW.

Fig. 1 shows the schematic circuit diagram of a block of this kind. It contains six silicon thyratrons, as well as the elements for overvoltage and overcurrent protection. The thyratrons are controlled by the associated pulse transformers which receive the control pulses from the control unit and, with galvanic separation, transfer them to the gates. The variation of the input quantity of the control unit allows the pulses to be displaced by up to about 180 ° with respect to time. Like the mutators and thyratrons, the controlled rectifier is able to operate as rectifier or inverter as a result of this pulse displacement.

Owing to its ability to operate as an inverter, this correcting element can give up power as well as

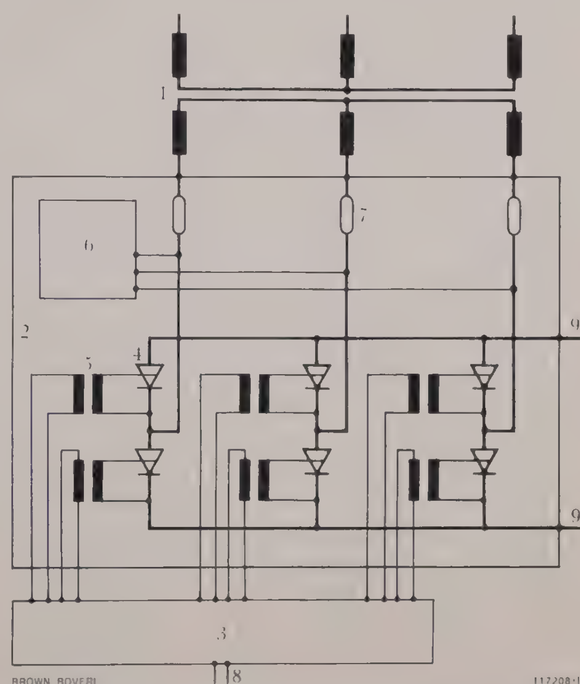


Fig. 1. – Simplified circuit diagram of a correcting element using silicon thyratrons

1 = Power transformer
2 = Silicon thyratron "building block"
3 = Control unit
4 = Silicon thyratron
5 = Control pulse transformer
6 = Overvoltage protection
7 = Fuse
8 = Low-power control input
9 = Power output

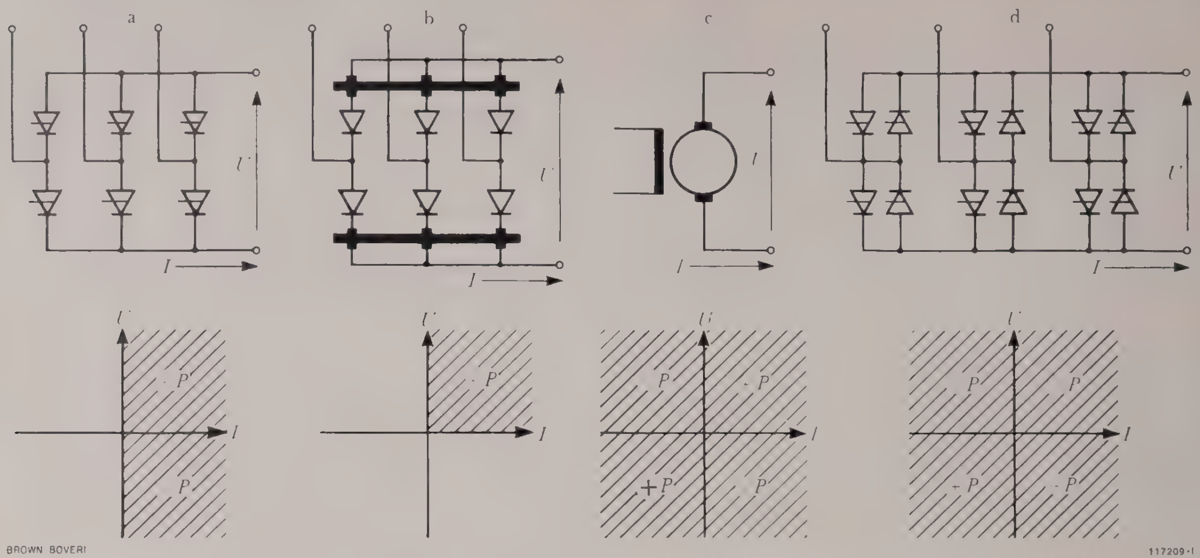


Fig. 2. – The sign of current, voltage and power with different correcting elements

Above: Circuit diagrams
Below: Power plane

U = Voltage
I = Current
$+P$ = Power output
$-P$ = Power absorbed

a: Set of silicon thyratrons for current in one direction. Voltage and power reversible.

b: Magnetic amplifier. Current, voltage and power are not reversible.

c: D.C. machine. All quantities reversible.

d: Silicon thyratrons in anti-parallel. All quantities reversible.

absorb it. It thus functions in two quadrants of the power plane (Fig. 2a). This property appears advantageous when comparing the silicon thyratron with the magnetic amplifier, which is also static, the latter only being able to operate in a single power quadrant (Fig. 2b). The controlled silicon rectifier may therefore be employed in those situations where the correcting element has to absorb energy temporarily from the controlled system, for example in rapidly de-energizing a magnetic field. If operation

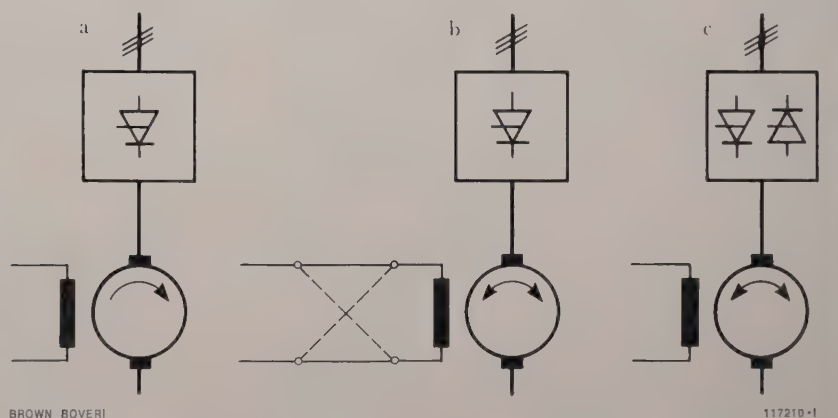


Fig. 3. – Alternative connections of a d.c. motor fed from silicon thyratrons

a: Armature fed with current in one direction, constant field; rotation in only one direction, no braking via the thyratrons.

b: Armature fed with current in one direction, the polarity of the field is reversible. Braking possible, rotation in either direction. Used for simple reversing drives.

c: Armature fed in anti-parallel. Rotation in either direction, braking possible. Used for reversing drives having to comply with stringent conditions.

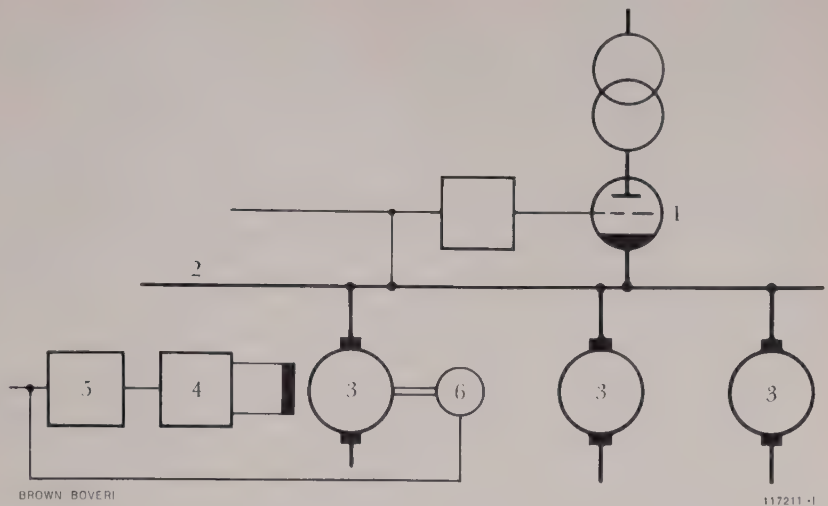


Fig. 4. – Field control of busbar-fed d.c. motors via silicon thyratrons as correcting elements

1 = Mercury-arc rectifier with constant voltage regulator
2 = Busbars
3 = D.C. motors
4 = Correcting element with silicon thyratrons
5 = Controller
6 = Tacho-generator

in all four quadrants of the power plane is required, possibly with a d.c. machine (Fig. 2c), the silicon thyratrons can be connected in anti-parallel, as shown in Fig. 2d for instance.

Like all controlled current-converting circuits, the correcting elements employing silicon thyratrons are almost instantaneous in their response. The sole time-lags—but in control circuits these are hardly of importance—are the dead-times resulting from the number of phases and, for example in a six-phase circuit operating at 50 c/s, amount to 3·3 ms at the most for only small variations in the control.

Like all other semiconductor elements of good quality, the silicon thyratron guarantees dependable service with a minimum of attention, since the life of the elements is, in principle, unlimited. Furthermore, silicon thyratrons have lower losses than gaseous-discharge valves, since their voltage drop in the forward direction is only of the order of magnitude of 1 V. As a result the design of the circuits can be compact, occupying a minimum of space.

The above properties of the silicon thyratron open up a wide field of applications for these elements in control engineering. The following remarks list some typical examples from practice.

Using six Brown Boveri high-power silicon thyratrons connected in a three-phase bridge circuit it is possible to attain a rated output of 50 kW, which is sufficient for variable-speed drives of medium capacity with direct armature feed. A drive of this kind is illustrated schematically in Fig. 3a. Since the silicon thyratron can reverse the voltage but not the current, this variant is only suitable for uni-directional torque. In those cases in which the drive has to be dynamically braked or the torque has to be reversible occasionally, the simple variant can be easily augmented by reversing the field (Fig. 3b). If the drive has to be braked, the armature current is temporarily blocked, then the field current reversed. As soon as the field has attained its desired strength in the opposite direction, the motor, which is still turning in the original direction, produces a negative armature voltage and can now be braked via the silicon thyratrons acting as an inverter; finally it is run up in the opposite direction by the thyratrons acting as rectifier. In conclusion Fig. 3c shows another variant with the silicon thyratrons connected anti-parallel. With this arrangement both the current and the voltage in the armature circuit can be reversed (see Fig. 2d). Thus the motor can be flexibly controlled in both directions, either as regards speed or torque. This arrangement, which involves twice as many valves, can be employed for reversing drives where stringent conditions have to be fulfilled.

Another interesting application of the silicon thyratron as a correcting element is for field control of busbar-fed motors (Fig. 4). Such drives for continuous processes are frequently connected to busbars supplied by mercury-arc rectifiers at constant voltage. The speed of the motors is controlled by varying the field. High-grade speed control of this kind demands very rapid response by the correcting element for

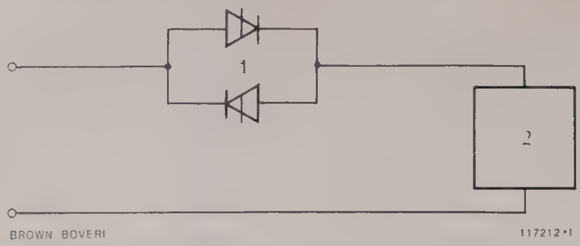


Fig. 5. – Control of an a.c. circuit by means of silicon thyratrons

1 = Anti-parallel silicon thyratrons
2 = Load circuit

the field and, above all, the ability to keep the speed constant by very rapid correction of the field in the event of load surges. Since, on large drives, the motor fields have quite a long time-constant, the correcting elements must be able to operate as inverters for a short time, to ensure that the field is weakened rapidly. Since the field current retains its direction, the temporarily negative excitation voltage rapidly corrects the motor field. For installations of this kind considerable success has been achieved in the past using mercury-vapour thyratrons, the operational experience gained having been excellent. Now that silicon thyratrons are also available, it is possible to choose the controlled rectifier which is most suitable in the circumstances prevailing in a particular application.

A further interesting application, shown in Fig. 5, can be used for controlling a.c. circuits. Connected in series with the load circuit are two thyratrons in anti-parallel, which conduct alternate half-waves of the supply. The power consumed by the load can be infinitely varied by controlling the two valves. This is an application which, using gaseous discharge valves, was adopted to a considerable extent for resistance welding machines and electronic dimmers (Thyralux).

The above brief notes on the applications of the silicon thyratron show that with this new element, the range of basic components which can be employed in correcting units has experienced an interesting extension. When selecting the most suitable of these elements—silicon thyratrons, silicon diodes with magnetic amplifiers, mercury-arc rectifiers or rotating machines—in a concrete practical case, it will be essential to weigh up the technical and economical aspects, so that the most suitable element can be adopted in every case.

(KME) R. ZWICKY

EMPLOYMENT OF THE BROWN BOVERI HIGH-POWER SILICON VALVES

621.382:546.28

Following a comparison of the technical properties of silicon diodes and thyratrons, their aptitude for certain specific applications is reviewed; thereby it is proved that silicon diodes are ideal for such applications as electrolysis plants and railway traction, while silicon thyratrons will primarily be used in control circuits involving low and medium powers.

THE TERM semiconductor valves may be taken to include both diodes and thyratrons. Sufficient has been said about the properties of these electrical components in the preceding articles. In this contribution it is consequently only necessary to underline their differences and certain features which govern their applications. Although all semiconductor valves possess a directional effect, i.e. only permit current to flow in one direction, with the thyratrons it is possible to control the moment at which it starts to flow. This difference in function has important consequences for practical employment because the flow of power in electric circuits can be controlled almost without loss. This, at first sight, appears to be such an advantage that one is tempted to believe that the thyratron, as the technically superior valve, will in time displace the diode. Nevertheless such a view is quite unjustified as it overlooks certain factors which will be dealt with later. At this point, however, it may be stressed that our verdict primarily applies to the present state of the art, although the standpoint for these considerations was chosen so as to permit the widest possible range of validity.

Technical Comparison of the Silicon Valves

The remarkable simplicity of their function and design is a characteristic feature of the semiconductor diodes, enabling them to be developed for very high directional powers without giving rise to intolerable manufacturing difficulties at the same time.

In contrast, the silicon thyratron involves a much more complicated design, which naturally adds to manufacturing difficulties and causes much heavier forward losses. Supposing, for instance, the same active cross-section were to be chosen for a diode and a thyratron, in order that the same cooler and casing could be used, the rated current of the thyratron would have to be made considerably lower than that of the diode, assuming the same temperature for the semiconductor wafer in both cases. Likewise the rated inverse voltage will be considerably lower for the thyratron than for the diode. The direct outcome of this is that the rated power of the thyratron is only about ¼ to ½ that of the diode, assuming identical geometrical dimensions. In non-steady-state operation the thyratron proves to have a lower overload capacity because its more complex construction and its higher forward losses favour local over-heating which, in contrast to the diode, does not result in an increased inverse current alone but also, under certain circumstances, can lead to the loss of the valve's controllability. Since future technological progress will be sure to benefit both types of valve to an equal extent, the more complicated construction of the thyratron will continue to keep the manufacturing costs higher than for the diode of comparable size. Finally, it must be borne in mind that the control function implies a wider range of characteristic values, involving more extensive testing and, naturally, broadening the scatter band of the product.

Summarizing, it may be established that diodes and thyratrons of the same size, with the same cooling facilities, cannot be subjected to the same electric loading. Compared with the diode, the thyratron

must have a considerably reduced power rating while, conversely, its price is bound to be higher, so its employment is only economical when the special advantages gained from its controllability are really able to take effect. This will primarily be the case when a wide control range or inverter operation is stipulated, and especially when high-speed control operations or inversion at high frequencies is required. The following remarks will therefore consider the question of which valve is most suitable for different fields of application.

Fields of Application for Silicon Valves

The following remarks will first of all deal with the fields in which rectifier equipment has hitherto been normally used, and will then proceed to those which may be included in the future as a result of the special advantages of the silicon valves. Beginning with the conventional fields, the first which comes to mind is electro-chemistry.

Electrolysis Plants

The supply of current to electrolysis plants is characterized by continuous operation at rated current with only slight variation to maintain constant current in the baths. To attain a good power factor the transformer is usually tapped and the voltage is varied discontinuously by a tap changer, with provision for continuous variation between taps, if needed. Since economic considerations and maximum efficiency are of prime importance in electrolysis plants, there is no doubt that diodes will be employed owing to their more attractive price and lower losses. The continuous voltage control can be effected by means of pre-magnetized chokes between the taps of the transformer, since there is no particular need for very rapid control. It is also possible to construct these control chokes with very low losses, as described on page 218.

If thyratrons were used instead of diodes, this would offer no advantages, in fact it would result in a number of disadvantages: the losses would be several times larger without any real benefit being gained in practice from the controllability; the price would be much higher and the installation would be far more complicated, owing to the extra control gear required.

Railway Traction Substations

Railways running on d.c. are normally fed from uncontrolled rectifiers. Remarkable features are the severe fluctuation of the load and the occasional short circuits which occur on the overhead contact wire and have to be cleared in such a manner that the railway service is not interrupted, if possible. For mercury-arc rectifiers the short circuit was usually extinguished by a system of blocking the grid, the rectifier operating normally without any retardation of the firing point and, only in the event of a short circuit, being blocked by making the grid negative for a fraction of a second. Such supply stations will therefore be equipped with diodes for preference because, in view of the heavy overcurrents and the occasional overvoltages from the supply network, adequate over-dimensioning is essential, which would render a thyratron installation more expensive, owing to its inherently lower overload capacity. The problem of clearing short circuits can be elegantly solved in the case of diodes, by using the shorting switch and the line circuit-breakers which are always provided.

The use of silicon thyratrons in such stations would only be justified if inverter operation for regenerative braking were specified. So far, experience has proved that this requirement is seldom made and therefore need not be considered further in this article.

Rectifier Locomotives

In recent years semiconductor diodes have been repeatedly employed on locomotives, owing to their small size and their insensitivity to temperature and vibration. Although diodes have been used almost exclusively so far, with tapped transformers and tap

changers for variation of the voltage, the idea of using silicon thyratrons has occurred on more than one occasion. Since plenty of experience has been gained with grid-controlled mercury-arc rectifiers on locomotives, the opinion is well founded, provided only the electrotechnical side of the problem is taken into account. Certain advantages, such as the particularly good behaviour during starting, and the ability to employ regenerative braking, are, however, offset by the drawbacks of the serious deterioration of the power factor and the greater harmonic content. Hence, without going into the questions arising out of the choice between thyratron and diode, it will be possible to assess the advantages and disadvantages solely by considering the electrotechnical aspect of voltage variation. This assessment, augmented by economic considerations as already mentioned for other applications, will probably result in the use of diodes for the majority of rectifier locomotives in future, control being effected by means of tap changers.

Control Systems

The principal feature of the remaining fields of application is the utilization of the property of variability by retardation of the firing point. Most of these applications are in no-loss control systems; in the past mercury-arc rectifiers have been used for large powers, and gaseous discharge thyratrons or magnetic amplifiers for small powers. Here it must be pointed out that, for large powers a combination—i.e. series and parallel connection—of silicon thyratrons will always be necessary. At present it is impossible to judge to what extent such a combination of a large number of silicon thyratrons will be technically preferable, that is to say, more reliable and cheaper, than mercury-arc rectifiers. For the next few years, though, without wishing to anticipate possible developments of the more distant future, it may be claimed that, for the range of high powers, the mercury-arc rectifier possesses properties which have not been bettered by any other kind of valve. Among these, mention may be made of recent developments which have resulted in an appreciable increase in the overload capacity from cold, and in the dependability.[1] It may therefore be assumed that the silicon thyratron will mainly be used in those cases for which the mutator tanks, with their type ratings, were too large and, on the other hand, where the magnetic amplifiers and gas thyratrons will in future cease to offer any technical superiority. In view of this, it is only natural that efforts have been concentrated on the design of "building blocks" with six thyratrons in a bridge circuit, as described in the preceding article on page 267. The advantage of this procedure is that risks, which are associated with all new methods, can be kept in reasonable bounds, by making the extent to which the units are employed in practice dependent on the amount of experience available at the time.

The smaller units, for which there are no problems of series or parallel connection to be solved, and also the question of protection is much simpler, can already be used for a wide range of tasks and will allow much valuable experience to be gained. This kind of application is also very interesting from the technical aspect, because the arrival of a new system adds to the competition which existing systems have to face, in which respect semiconductor and gaseous discharge valves will probably supplement one another harmoniously in the range of low and medium powers. In this particular case it is unlikely that the new technical variant will simply supersede the existing ones, but that each will find its own limits in the course of time, and that one will augment the other; owing to the width of the power range this is easy to understand.

Concluding Remarks

Although a technical prediction, like any kind of prognosis, essentially involves an inevitable amount of

[1] E. H. LUDWIG: Entwicklungstendenzen und Probleme beim Bau von Quecksilberdampf-Stromrichtern. Elektrotech. Z. 1960, Vol. 81, No. 25, p. 903–13.

uncertainty, the engineer is obliged to consider the future situation and coming developments in order to create a firm foundation for his planning. The degree of uncertainty will then be less, the fewer the unknown factors and uncontrollable factors he takes into account. Consequently, in the present case the assessment was deliberately based on only a few assumptions, with the result that, although only a rough idea can be gained of the general trend, we may at least hope that our conclusions are reasonably accurate.

(KME) T. WASSERRAB

BRIEF BUT INTERESTING

Brown Boveri Silicon Rectifiers in a Traction Substation of the Oberrheinische Eisenbahn-Gesellschaft (OEG), Mannheim, Germany

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IN the densely populated triangle formed by Mannheim, Heidelberg and Weinheim, the OEG has to handle very heavy rush-hour traffic, as well as tourist traffic, for which motor-coach compositions are employed, running off 660 V d.c. in urban areas and 1200 V on the cross-country sections of the network. The contact wire is fed from the substations at Mannheim–Käfertal, Rheinau, Seckenheim and Schriesheim which, in line with technical progress, were originally equipped with water-cooled mercury-arc rectifiers, then with pumpless Brown Boveri units. The first water-cooled tanks, installed in 1927, are still in service in Seckenheim; in fact one of them has never been opened or overhauled.

The steadily increasing traffic in the area between Mannheim and Neckarau induced the OEG to build a new substation in 1959, in which the first Brown Boveri silicon rectifier for traction service is installed. The station was commissioned about the middle of October 1960. The following is a brief review of its principal features.

Technical Details of the Substation

On the high-voltage side the substation is connected to a closely meshed 5-kV network supplying the industrial premises concentrated in the Neckarau suburb of Mannheim. In the basement is the 5-kV switchgear; on the ground floor is the silicon rectifier cabinet, the pumpless mercury-arc rectifier and the d.c. switchgear, with two control panels, a metering and coupling panel, as well as two line feeders with d.c. circuit-breakers. The rated data of the silicon rectifier are as follows:

Current—1250 A, IEC rating class IVb

Voltage—660/825 V (full-load voltage at the substation)

Power—1030 kW

The associated transformer, with a vector-group symbol of Yd 5, is designed for 730/915 V with an impedance voltage of about 6/7·7% and contains the means for changing the internal connections to allow for the future increase from 660 to 825 V in the line voltage. Its rating in kVA corresponds to about 80% of the rated sustained output of the associated rectifier unit, which experience has proved to be adequate in traction installations.

The data of the parallel mercury-arc rectifier unit (type rating 1000 A) have been adapted to the step-down ratio of the transformer and the impedance voltage of the silicon rectifier to ensure that the current load is adequately spread between the two rectifiers, even at partial loads.

Fig. 1 shows the mercury-arc rectifier rated 1000 A at 825 V, complete with its undercarriage and auxiliaries, with the silicon rectifier cabinet standing beside it. The latter does not stand on a plinth as the air required to dissipate the heat losses of the diodes and busbars—amounting to about 10 kW at 1250 A—is drawn in from the cellar through an opening in the floor immediately below the cabinet. The fans inside

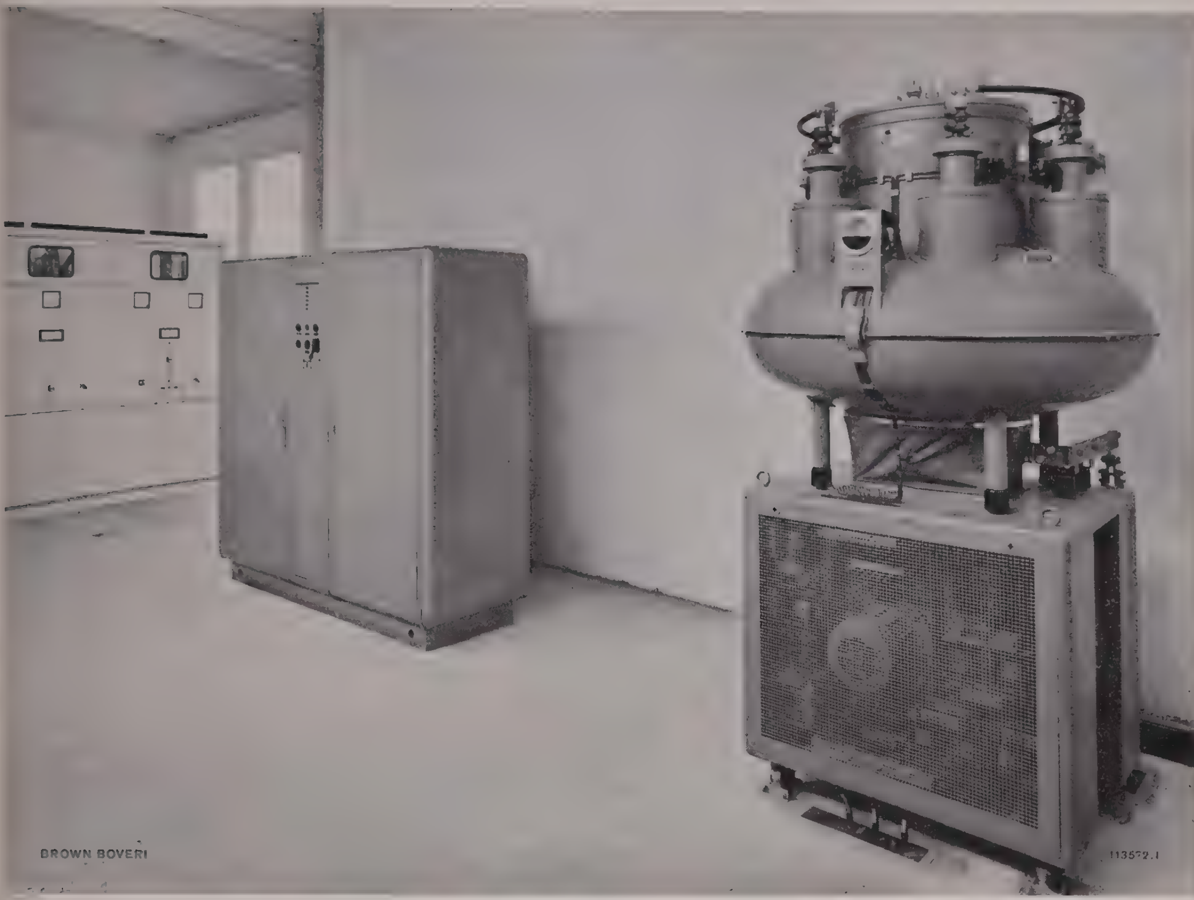

Fig. 1. – Traction substation of the Oberrheinische Eisenbahn-Gesellschaft (OEG), Mannheim, Germany

showing the silicon rectifier (left) rated 1250/2500 A at 825 V, operating in parallel with a mercury-arc rectifier (right) rated 1000 A at 825 V.

the cabinet force the warm air out through the back. The rectifier unit contains 60 silicon diodes in a three-phase bridge connection and is equipped with the protective combination described on page 191, with shorting switch and d.c. circuit-breaker. The shorting switch, which can be seen at the bottom of the open cabinet illustrated in Fig. 2, is used to protect the diodes:

- In the event of an internal short circuit, which can only occur in the very unlikely case of two diodes in series in the same limb of the bridge becoming defective at the same time. If only one diode becomes faulty—ceases to block—a visual signal is given.
- In the event of short circuits on the busbars or very close to the station on the line, where the short-circuit current may harm the diodes. All other line shorts are cleared by the breakers.
- In the event of a backfire in the parallel mercury-arc rectifier, provided this develops into the most unfavourable case of a persistent arc. This then corresponds to the preceding case of the short circuit on the busbars.

If an internal short circuit occurs, the shorting switch is actuated by the six reverse-current transformers incorporated in the cabinet; in the event of a busbar short, by an impulse current transformer. The time-lag between the occurrence of such a fault and the closure of the shorting switch amounts to about 2·5 ms. If the shorting switch is actuated by an external short circuit, it can be reset from the remote control room as it is equipped with a servo-motor.

The station has operated unattended since it was commissioned. At the present moment it is being equipped for control over a v.h.f. link. The feeders are

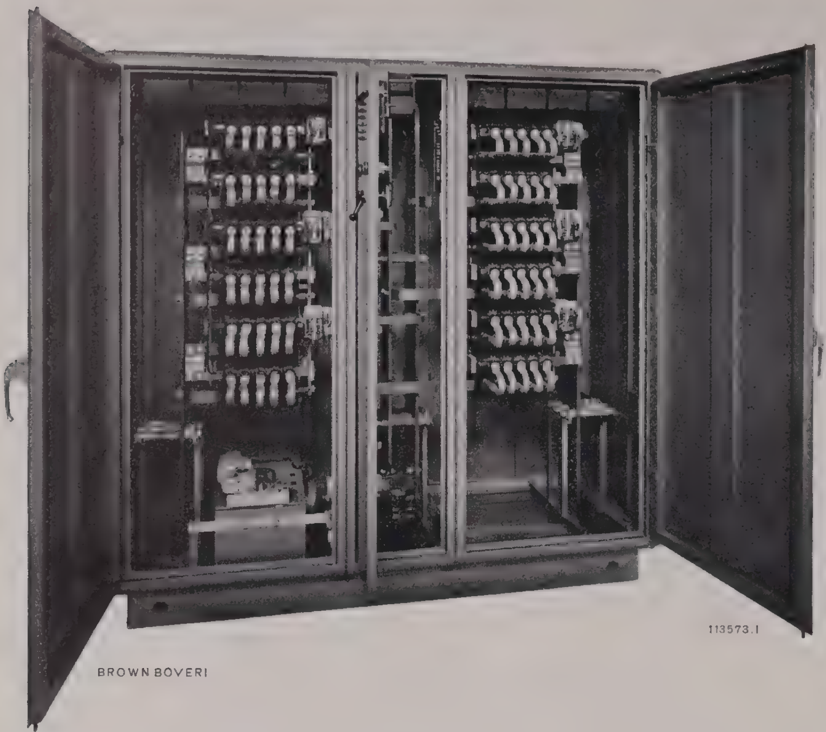

Fig. 2. – Cabinet of the silicon rectifier, with the doors open

feeding the contact wire at 825 V, 1250/2500 A.

equipped with automatic line-testing devices which only lock out the line breakers when three unsuccessful attempts have been made at reclosure following a line short circuit.

Future Prospects

Experience gained so far indicates quite clearly that there is nothing to prevent silicon rectifiers from being used to feed the contact wire of traction systems. It is, of course, essential to fulfil the conditions imposed by the physics of semiconductors, by the nature of the load in traction service, and by the requirements respecting the selectivity with which faults are interrupted. As a result of the excellent results obtained with the first silicon rectifier, the OEG have ordered a second unit from Brown Boveri, rated 1000 A at 1200 V, to replace a mercury-arc rectifier.

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D.C. circuit-breakers type ID protecting silicon rectifiers in a large chemical works

Each feeder from a double rectifier set is protected by its own breaker.

BROWN BOVERI

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